TUNNEL CONSTRUCTION BY PERIPHERAL SAWING AT THE FORT RANDALL RESERVOIR, PICKSTOWN, S. DAK.

BY WALTER E. LEWIS

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by

Walter E. Lewis[1/]

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INTRODUCTION AND SUMMARY

The Fort Randall Reservoir project, on the Missouri River at Pickstown, S. Dak., was designed by the Corps of Engineers and is part of the Missouri River Basin Development Program. The location of the project with respect to adjacent features is shown in figure 1.

When the project is finished, it will include a large earthwork dam and 12 circular tunnels, 8 of which will be equipped for power and 4 for flood control. Various phases of the construction have been contracted to independent companies, and at present four companies are working on different phases of the project under a rigid time schedule. Western Contracting Corp. is the contractor on stage II, earthwork; Johnson-Winston Construction Co. is the contractor for construction of the intake towers at the upstream side of the dam; McCarthy Improvement Co. has the contract for the power house and the outlet works on the downstream side; and Silas Mason Co. has the contract for driving the power and flood-control tunnels. The latter two companies use the same roads for ingress and egress to their respective work areas and the same general waste dump area. Under such circumstances, it is necessary that each company stay on a time schedule in regular sequence to avoid interference with the other.

Each contracting company must confine all work to its alloted area or arrange for concession from the other contractor, which Silas Mason Co. was able to do in the initial part of its operations. Later, the tunnel contractor had to limit his operations to his alloted area, and this has presented several problems in traffic control for both contractors. Excavation of three tunnels usually is in progress at any given time; eight of the tunnels are so situated that they can be served by only 37 feet of roadway (fig. 2), which is on a lower bench of and parallel to a chalk cliff. Track is laid on this roadway, and all drill and tunnel support jumbos, trucks, mucking machines, and other needed equipment must pass over it for entrance to the various tunnels at exactly timed intervals. The roadway is kept level and in good repair by a road grader that moves over it two to three times during the day shift, but only when it does not interfere with excavation operations, and then in and out quickly so that it will not disrupt the cycle of operations.

All the tunnels have been, or will be, started from the downstream side of the dam and driven their full length of 873 feet on a 1-percent rising grade to the upstream side. The tunnels are numbered consecutively from 1 to 12, beginning next to the river. Numbers 1 to 8, inclusive, will be power tunnels, and 9 to 12, inclusive, will be used for flood control. The first eight tunnels are excavated to a 33-foot diameter and lined with concrete to a finished 28-foot diameter for a distance of 658 feet. The remaining 215 feet will be excavated to a 26.5-foot diameter and finished with

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concrete to a 22-foot diameter. A steel penstock will be placed in the initial, or downstream, 658 feet. Tunnel 10 has the same dimensions as tunnels 1 to 8, and the bore of the remaining three tunnels remains the same throughout their length; the evcavated diameter is 26.5 feet and the finished diameter is 22 feet. Figure 2 shows tunnel entrances into the chalk cliff from the lower bench roadway.

All the tunnels are in the lower member of the Niobrara chalk formation at an elevation of 180 feet below the crest of the dam. Figure 3 shows the location of a tunnel with respect to the crest of the dam. The Niobrara chalk consists of two members - the upper, known as the Smoky Hills, and the lower, known as the Fort Hays. At this point the Fort Hays member is 74 feet thick and uniform in character. It is a firm, light-gray, mottled chalk having the following general chemical and physical properties:2/

Chemical composition, percent		Physical properties	
Silicon dioxide	18.70	Dry density, lbs./cu.ft. ...	113.3
Aluminum oxide	9.78	Moisture, percent	15.0
Calcium oxide (CaO) ..	34.90	Compressive strength, p.s.i.	1,500
Sulfate (SO_3)	.60	Direct shear, p.s.i.	140
Carbonate (CO_2)	26.3		
Other oxides	4.1		
Water released between 105° C. and 1,200° C.	5.8		

A distinct bentonite marker 1-1/4 inches thick occurs in the Fort Hays member at 19 feet above the bottom of the tunnels. Fault and joint planes are numerous, and it is not unusual for large blocks of chalk to slide out of the face on these planes; therefore, the face of the tunnel must be scaled down carefully after blasting.

The tunnels are on 70-foot centers; thus, a chalk barrier 37 feet thick is left between tunnels. During excavation, the entire length of the tunnel is driven and supported with steel before the concrete lining is poured. At this writing (November 1950) all but one of the tunnels have been holed through, and the concrete lining is being poured. When a tunnel is being excavated adjacent to one being lined with concrete, excavation must not be closer than 100 feet measured along the tunnel axis, to 7-day-old concrete in the adjoining holed tunnel.

Specifications required that the tunnels be either line-drilled or sawed before any blasting was done. Silas Mason Co. tried both peripheral drilling and peripheral sawing. Peripheral drilling was first tried. It consisted of drilling 5-inch-diameter holes on 10-inch centers outside the circumference margins of the tunnels. Approximately 120 holes were spaced around the periphery of the tunnel, and an 8- to 9-foot depth round was broken. Later, peripheral sawing was initiated.

2/ Information courtesy of John Trantina, Chief, Engineering Division, Corps of Engineers, Fort Randall Reservoir project, Pickstown, S. Dak.

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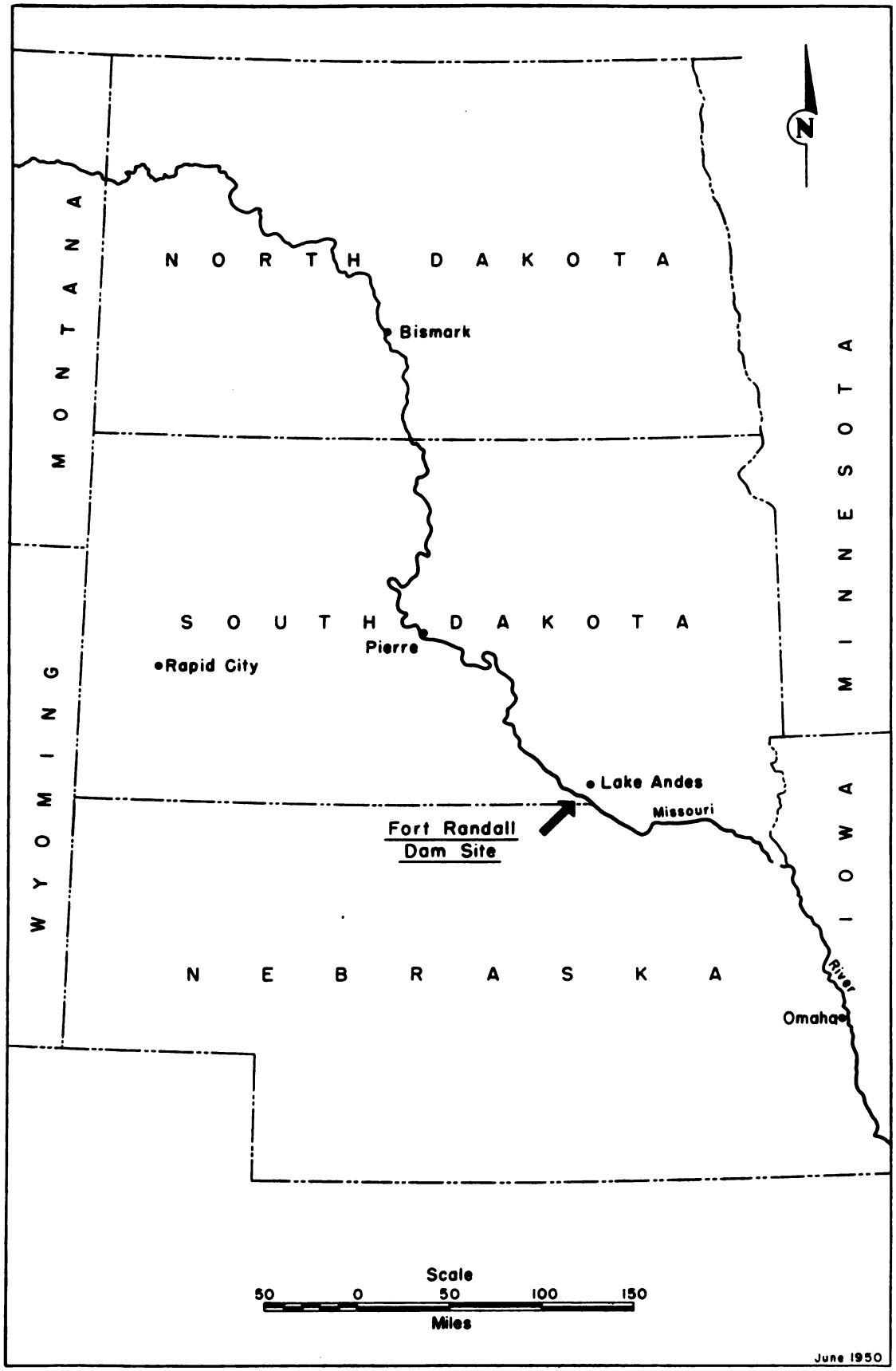

Figure 1. - Location map.

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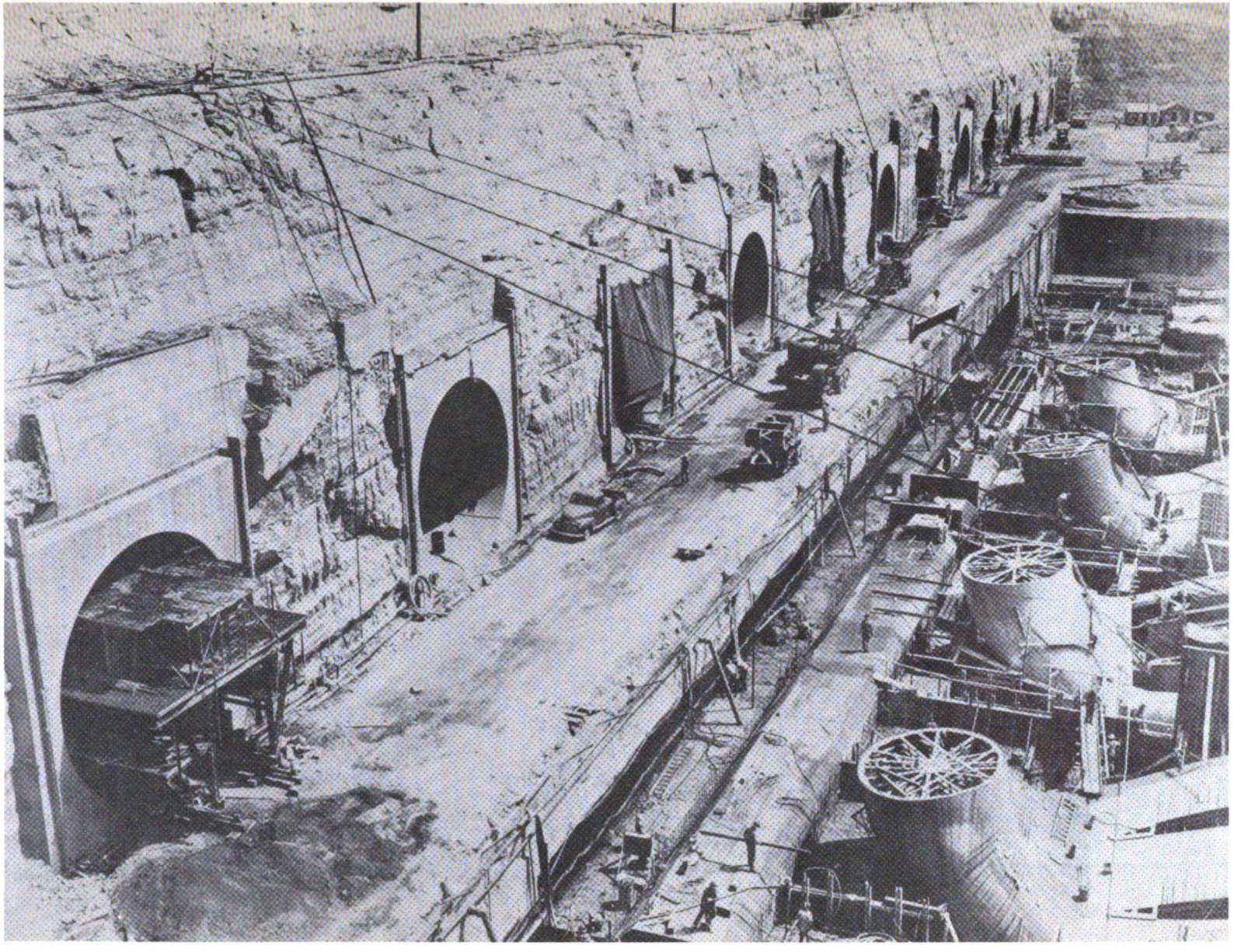

Figure 2. - Tunnel entrances into the chalk cliff from the lower bench roadway.

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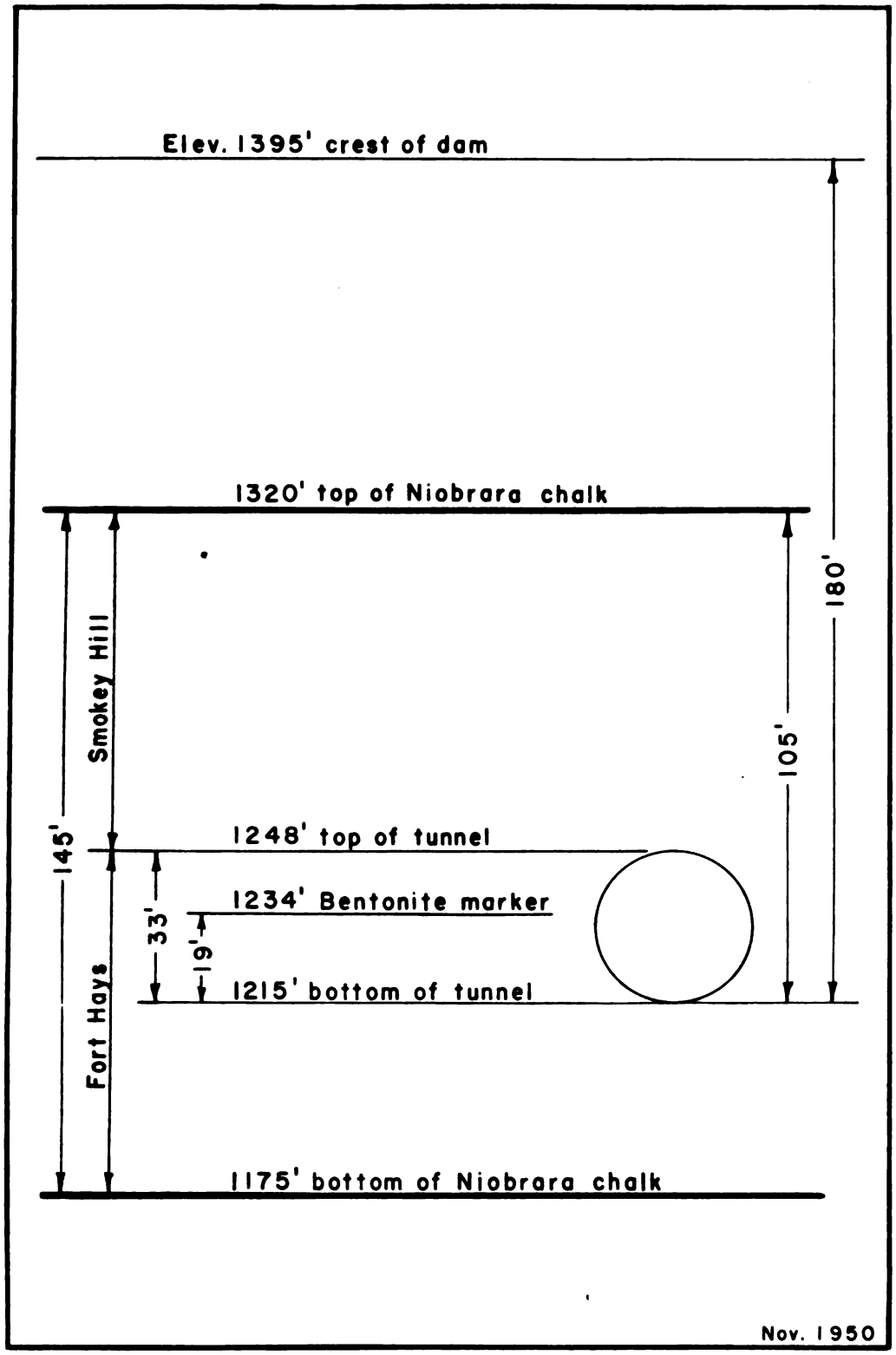

Figure 3. - Location of tunnel with respect to crest of the dam.

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Peripheral sawing was first attempted by Silas Mason Co. in the tunnels at Fort Peck Dam, Mont., but without success; however, the experiments with the saw were continued at Fort Randall and, finally, a machine was constructed that would cut a 6-inch kerf to a depth of 8 to 9 feet around the periphery of the tunnel.3/ The outside periphery of the circular tunnels was left smooth and unbroken, and over-all progress was speeded.

Significant improvements were made in the design of the sawing machine over the type first developed at Fort Peck Dam. Operating troubles were corrected gradually until with skilled operators, the peripheral sawing of a tunnel became free from unusual breakdowns or annoyances.

This paper describes the peripheral sawing method.

ACKNOWLEDGMENTS

The cooperation of the following officials at the Fort Randall Reservoir Project, Pickstown, S. Dak., in the preparation of this report is gratefully acknowledged:

R. B. Jewell, resident manager, Silas Mason Co.
George Evans, area engineer, Corps of Engineers.
John Trantina, chief, Engineering Division, Corps of Engineers.
D. S. Waddy, Jr., electrical superintendent, Silas Mason Co.
George L. Lyle, general superintendent, Silas Mason Co.

Many of the data contained herein were obtained from personal conversation and discussion with Mr. Jewell. Thanks also are due Mr. Jewell and Silas Mason Co. for furnishing all drawings and photographs used in the manuscript.

Acknowledgment is also made to Dr. Edward L. Tullis, Head, Geology Department, South Dakota School of Mines and Technology, for the use of a preliminary report on the Fort Randall excavations written for the Bureau of Mines from information gained from a personal conversation with Mr. Jewell in October 1949.

PLANT EQUIPMENT

As is usual on many large construction contracts, the contractor has built considerable equipment for use only on these tunnels. All jumbos constructed for drilling and placing tunnel supports have been designed to fit the tunnel specification requirements and must be completely amortized on this contract.4/ The large, specially built equipment aids in keeping the job moving smoothly and efficiently and enables the contractor to meet the rigid time schedule of the Corps of Engineers. The total Silas

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3/ Method and apparatus for tunnel excavation by saw invented by R. B. Jewell, Resident Manager, Silas Mason Co., Fort Randall Reservoir Project, Pickstown, S. Dak., and covered by Patent Application Serial No. 133583.

4/ All special equipment designed by R. B. Jewell.

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Mason Co. plant at Pickstown cost about $1,000,000 in material plus $500,000 to erect. The plant equipment used directly in excavation of the tunnels is discussed below.

Power Plant

Power is generated at 2,400 volts by a Diesel-electric plant situated on the downstream side of the dam, consisting of three 600-kw. generators, one of which is a standby. The voltage is stepped down to 440 volts, 3 phase, and 110 and 220 volts, single phase, by transformers above the tunnel portals. Current is transmitted from the power plant to the downstream portals and into the tunnels in 3-conductor cables, hanging on the steel tunnel-supporting ring beams within the tunnels.

Compressed Air

Compressed air is supplied by four 500-cubic-foot portable compressors also situated on the downstream side of the dam. Air is brought to the tunnel faces through a 4-inch pipe and thence through 4-inch rubber hose to an air receiver on the drill jumbo. The compressed air is transferred from the receiver on the jumbo to 2-inch standpipes on the jumbo that have several outlet valves along their length. Two-inch drilling-machine hoses are connected to these outlets.

Trackage

Rail weighing 60 pounds per yard is used where track is required. The lower bench and the tunnels are equipped with both wide-spaced tracks for the jumbos and standard-gage tracks for battery locomotives and Conway mucking machines. Switches in the standard-gage track on the lower bench roadway permit the mucker to be switched over to the tunnel tracks. The curves are gradual into each tunnel, and the switchover is made easily.

Ventilation

The tunnels are ventilated by two 15,000 c.f.m. fans driven by 40-hp. electric motors. The air is supplied to the headings through 24-inch pipes, one on each side of the tunnel. The pipes are carried to within 100 feet of the face. The complete motor and fan unit is enclosed within the pipe. Normally, the fans blow air into the tunnels, but they can be and are reversed by reversing the motors to draw gases from the tunnel after blasting.

CYCLE OF OPERATIONS

Tunnel excavation consists of a definite cycle of operations performed in three separate and distinct parts, and these have been developed and translated into action by careful planning by the engineering staff of Silas Mason Co.5/ They are (1) sawing and drilling an 8- to 9-foot round, (2) placing tunnel supports, and (3) mucking. As many as four tunnels have been driven at one time. While one part of the cycle is in progress in one tunnel, a different part of the cycle is in progress in another tunnel.

5/ Cycle of operations developed by R. B. Jewell.

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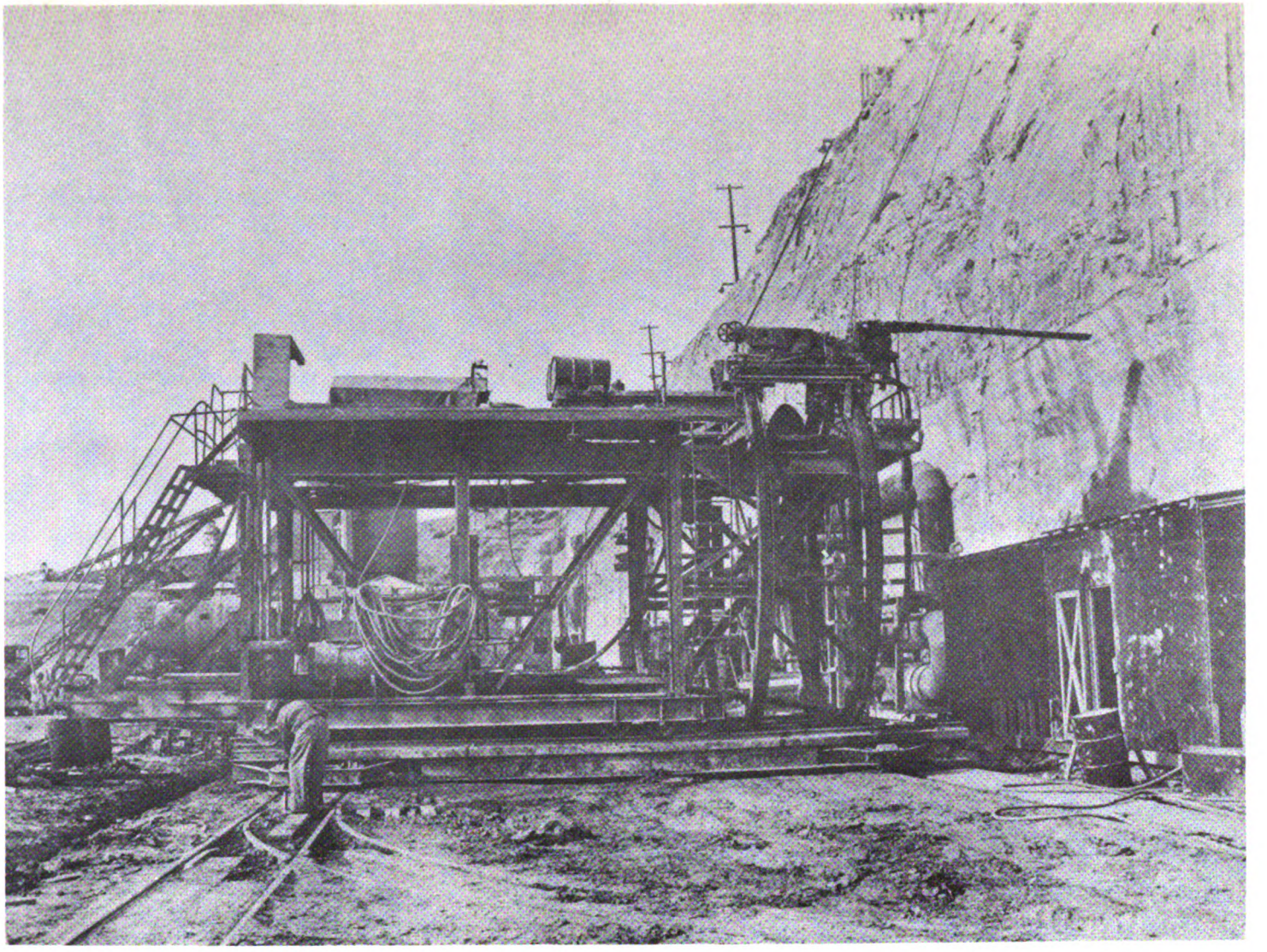

Figure 4. - Transporting the small drill jumbo on the jumbo carriage along the lower bench roadway. (Method and apparatus for tunnel excavation by saw invented by R. B. Jewell, resident manager, Silas Mason Co. and covered by Patent Application Serial No. 133583.)

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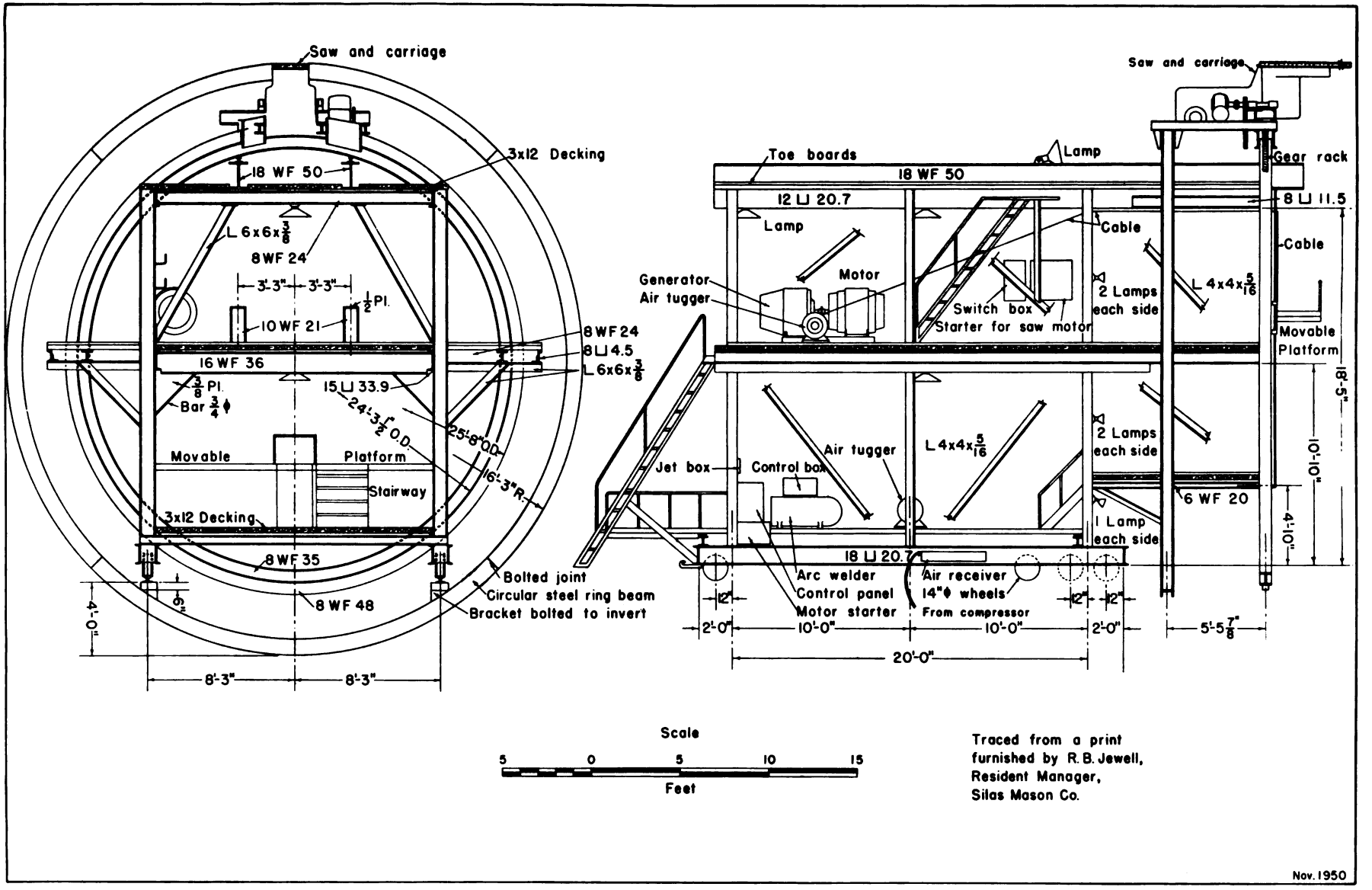

Figure 5. - Large drill jumbo.

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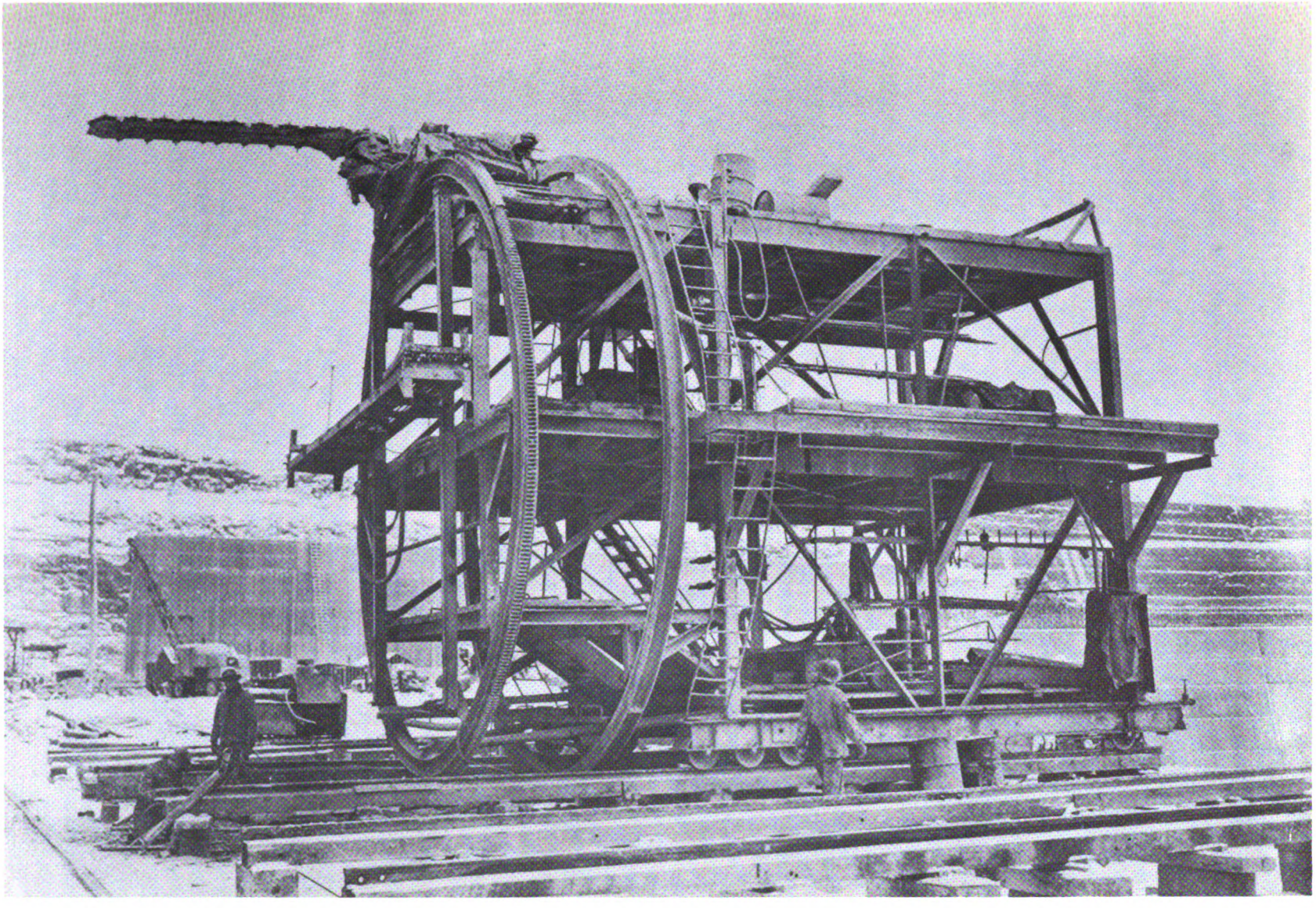

Figure 6. - The large drill jumbo in the storage area. (Method and apparatus for tunnel excavation by saw invented by R. B. Jewell and covered by Patent Application Serial No. 133583.)

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Sawing and Drilling

Sawing and drilling actually consist of (1) peripheral sawing and blast-hole drilling simultaneously and then (2) mucking of the rock dust or cuttings result from sawing.

The rotary saw is mounted on a jumbo, which is moved into the tunnel on the wide-gage track. The size of the jumbo depends on the cross section of the tunnel being excavated. Jumbos move on rail in only two directions - in and out of the tunnels. For moving at right angles to these directions, it is necessary to run them upon a carriage, which runs on a transfer track extending along the roadway in front of the tunnel portals. Figure 4 shows the small drilling jumbo used in excavating the transition parts of the tunnel being transported along the roadway on the transfer carriage. The top of the carriage is fitted with wide-gage tracks corresponding to the width of the tracks in the tunnel, and the jumbo is run onto the carriage from a storage area or on exit from a tunnel. The tracks for the mucker and battery locomotive are seen in the left foreground.

The large drill jumbo used in excavating the 33-foot-diameter portion of the tunnels is constructed by joining together three steel sections, each of which is composed of two parts 10 feet 10 inches high by 10 feet long by 16 feet 6 inches wide, one part set vertically upon the other. The front section, which contains the saw unit, circular I-beam, circular ring gear, and movable drillers platform projects out beyond the double-flanged front wheels of the jumbo. The jumbo travels on rails spaced 16 feet 9 inches, measured center to center. Figures 5 and 6 are a detailed drawing and a picture of the large drill jumbo. The small drill jumbo is similar to the larger one, except that it is lower in height and constructed in one section. The saw unit, circular I-beam, circular ring gear, and movable drilling platform project out beyond the double-flanged front wheels. Figure 4 shows the small drill jumbo being transported along the lower bench roadway. Steel supports are installed to within 14 feet of the tunnel face at all times, and the front of the jumbo projects far enough beyond the wheels to permit the saw to reach the face. As most of the weight is concentrated in front, the jumbos are equipped with three wheels in front and one wheel in back on each side. The three wheels in front also allow the jumbo to be advanced toward the face, with two of the front wheels run off the ends of the tracks.

The large jumbos have three wooden decks. An air receiver is situated underneath the first deck. The control panel for the electric motor that runs the saw, an arc welder, and an air tugger are on the first deck. The air tugger is used for maneuvering the jumbo into final position in peripheral sawing operations. The second deck contains the motor-generator set, which was used for running D.C. electric coal augers when the tunnel was advanced by peripheral drilling, as well as a switch box and starter for the motor-generator and another air tugger, which is used for manipulating the movable platform that projects out ahead of the front of the jumbo. This movable platform is used for drilling the blast holes, and it is readily movable to any elevation desired. The third and upper deck is used as a service deck to reach the crown of the tunnel and also for arc welding the joints of the circular ring beams that are used for tunnel support. The drill

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jumbo is also equipped with lights, racks for the drill steel, and 2-inch standpipes, on which there are several outlets for compressed air.

Peripheral Sawing

The saw is a slabbing coal saw mounted on a carriage on the front of the jumbo. The carriage and saw move as a unit about the periphery of the tunnel on a circular ring gear attached to the front end of the jumbo. The cutting element of the saw is driven by a 75-hp. electric motor, and the entire unit is moved about the circular ring gear by a 10-hp. compressed-air motor. The head on the cutter bar of the saw is constructed so that it can be shortened 15-3/4 inches from the maximum outer diameter of its own circle, and this allows the cutter bar to be retracted inward toward the center of the tunnel and permits the jumbo to move into and out of the tunnel past the supporting steel. Figure 7 shows a front view of the saw and carriage. The screw that retracts the head on the cutter bar is seen at left of center. The saw lies flat against the rock and cuts a ring 33 feet in diameter, 5-1/2 inches wide. To place the saw against the rock, it is necessary that at least 14 feet from the face of the tunnel be left unsupported so that the saw can have free, unrestricted entry to the tunnel face.

The normal procedure for starting peripheral sawing is to retract the cutter bar and move the jumbo into preliminary position at the tunnel face with a bulldozer. The jumbo is placed in final position with the tugger hoist on the jumbo by attaching the cable from the hoist to the steel tunnel support. The jumbo is then moved forward until the head of the cutter bar fully clears the circular steel supports. To place the saw in cutting position, the cutter bar is moved into its outermost position, and the jumbo is moved slowly forward by the tugger until the teeth of the saw are touching the chalk face of the tunnel. The 75-hp. electric motor that drives the cutting element of the saw is started, and the cutter bar is placed in position on the lower right side of the tunnel. Only the cutting element is kept operating in this position with the carriage stationary. The saw is sumped into its full depth of 8 to 9 feet by moving the jumbo forward with the tugger hoist.

When the desired depth is reached, the jumbo is solidly braced, and with the cutting element of the saw rotating on the cutter bar at full speed, the carriage is started in a clockwise direction on the circular ring gear by use of the 10-hp. air motor. Figure 8 shows the saw in operation after it has been sumped in. The saw moves clockwise at a maximum speed of 18 inches per minute. If the ground contains hard pyritic concretions, the speed drops below the maximum, but usually full speed of advance is maintained throughout the full circle cut. The head in cutting position on the cutter bar can be seen in figure 8.

When the saw reaches the lower left corner, the circular motion of the carriage is stopped, and the jumbo is backed, withdrawing the saw from the cut. The saw is then moved clockwise approximately 18 inches and is sumped in again, and cutting is resumed. A corresponding block is left on the lower right side. These uncut sections of chalk serve as support for the solid

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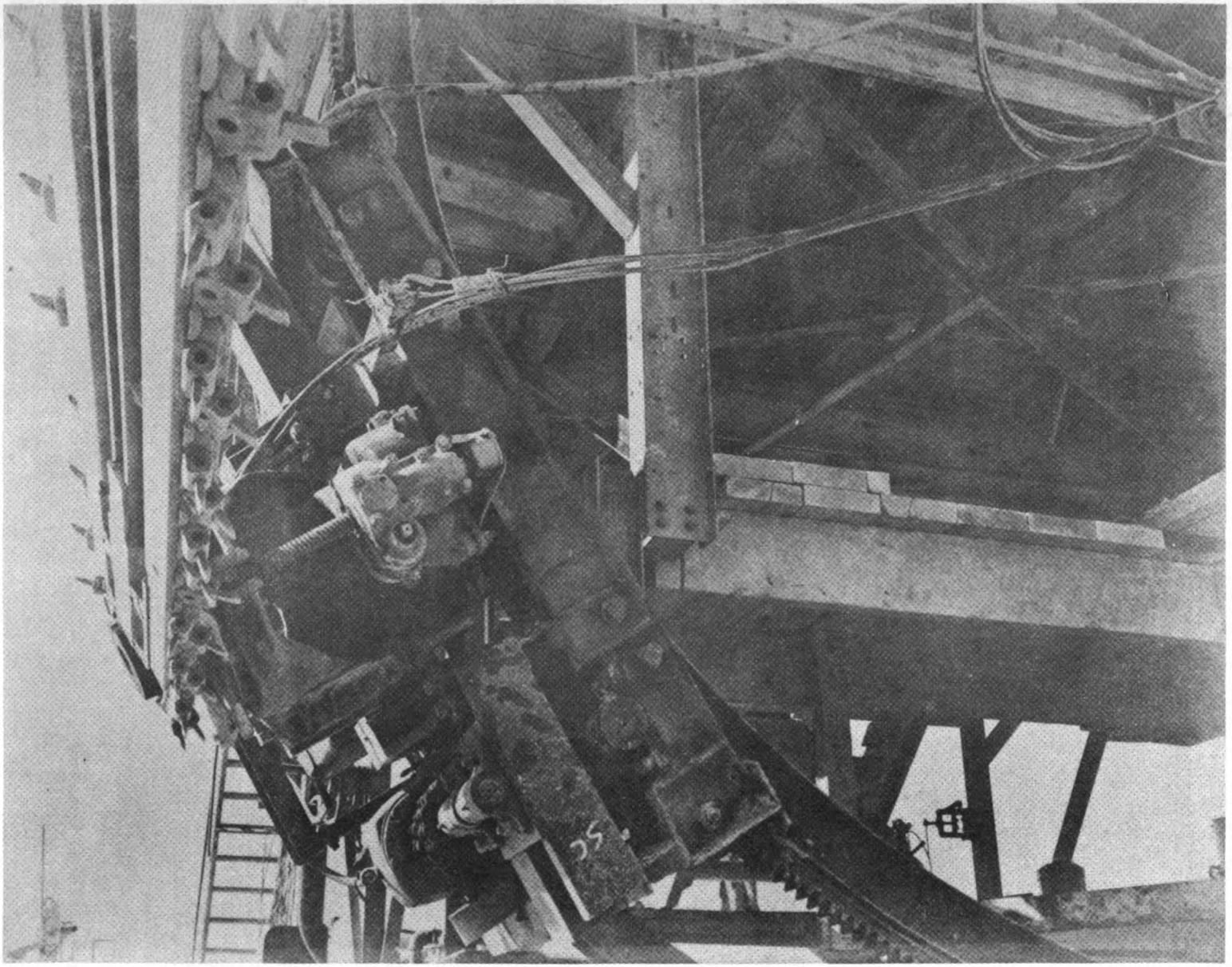

Figure 7. - Front view of the saw and carriage. (Covered by Patent Application Serial No. 133583.)

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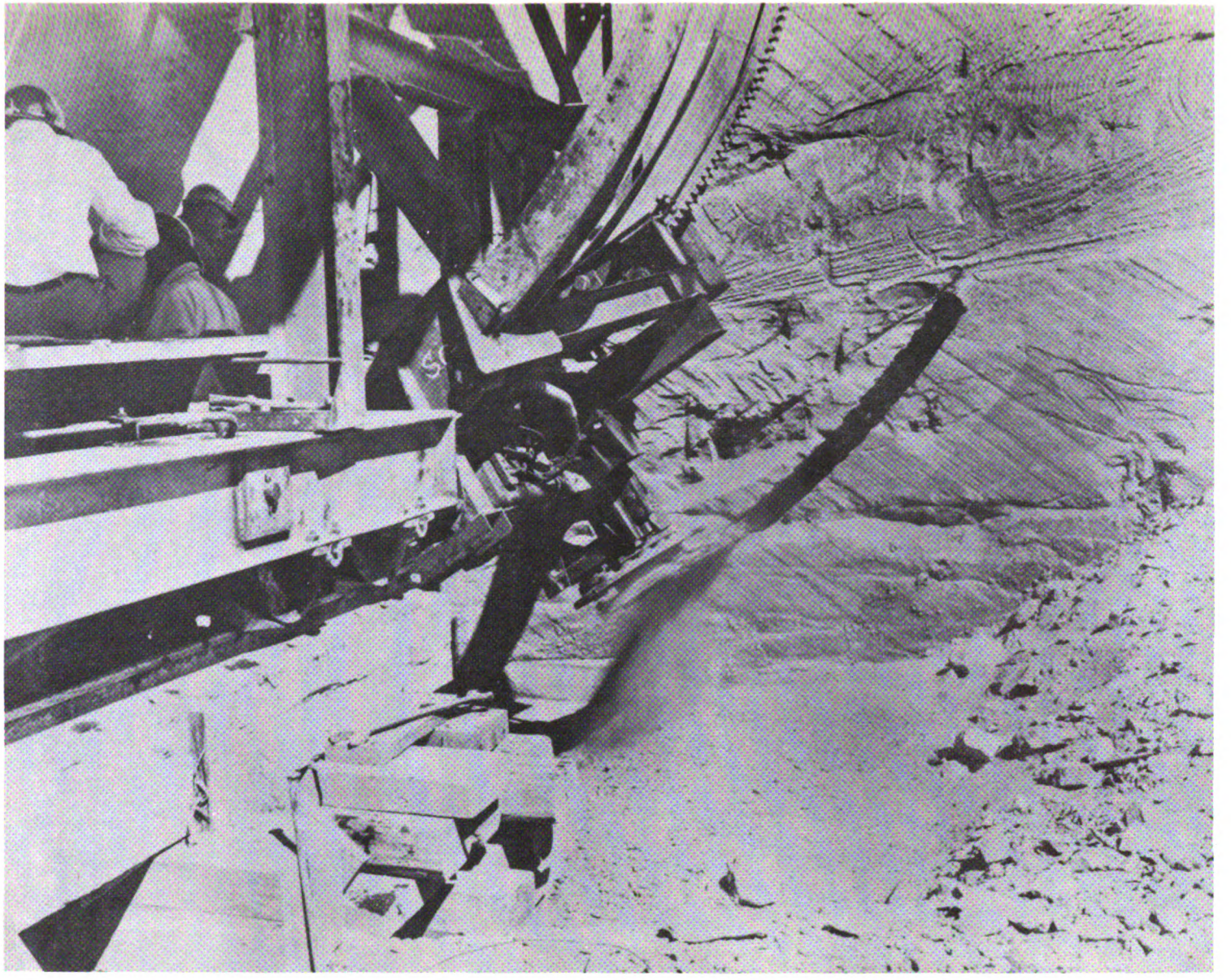

Figure 8. - Saw in operation. (Covered by Patent Application Serial No. 133583.)

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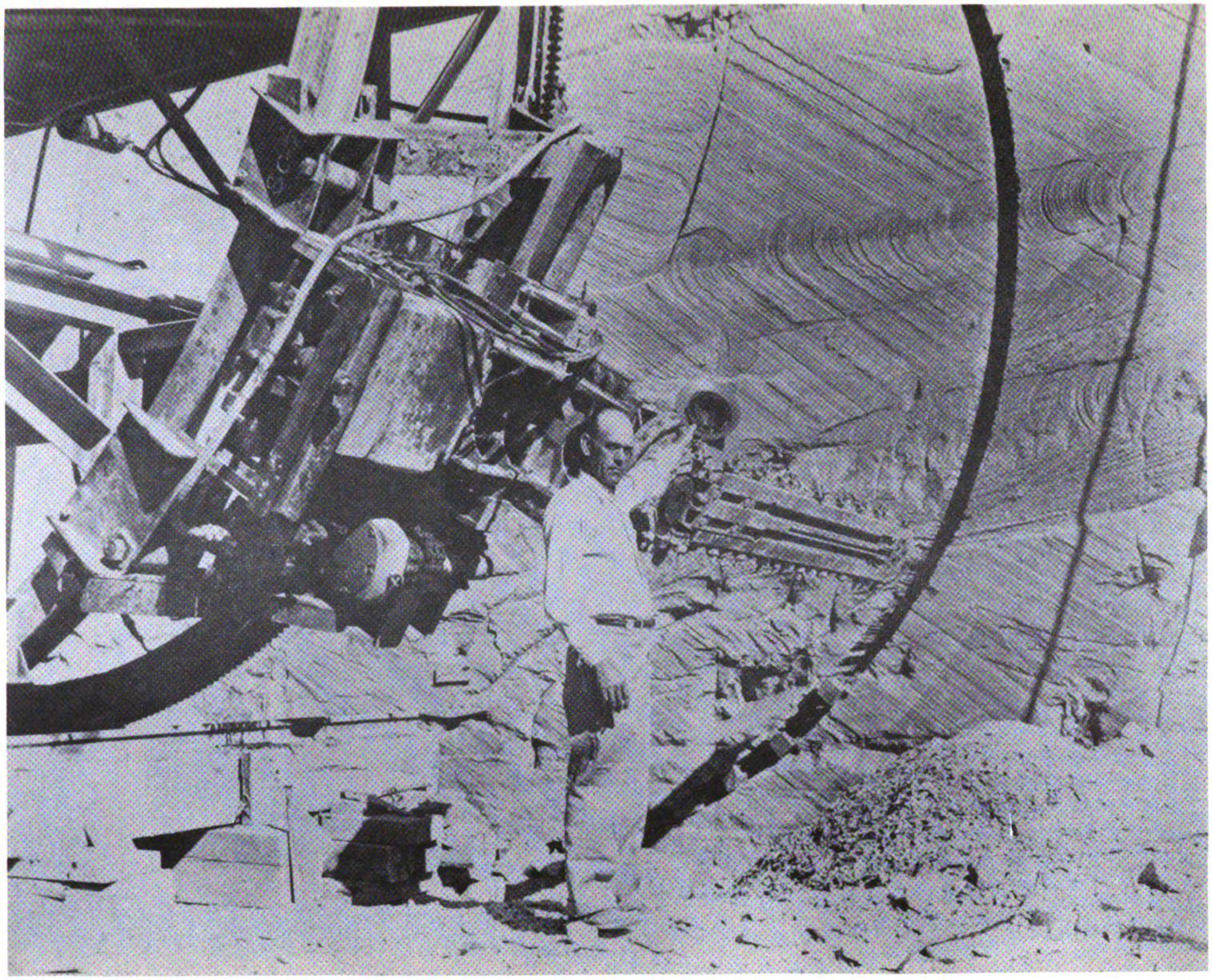

Figure 9. - Cut made by peripheral sawing at entry to tunnel. (Covered by Patent Application Serial No. 133583.)

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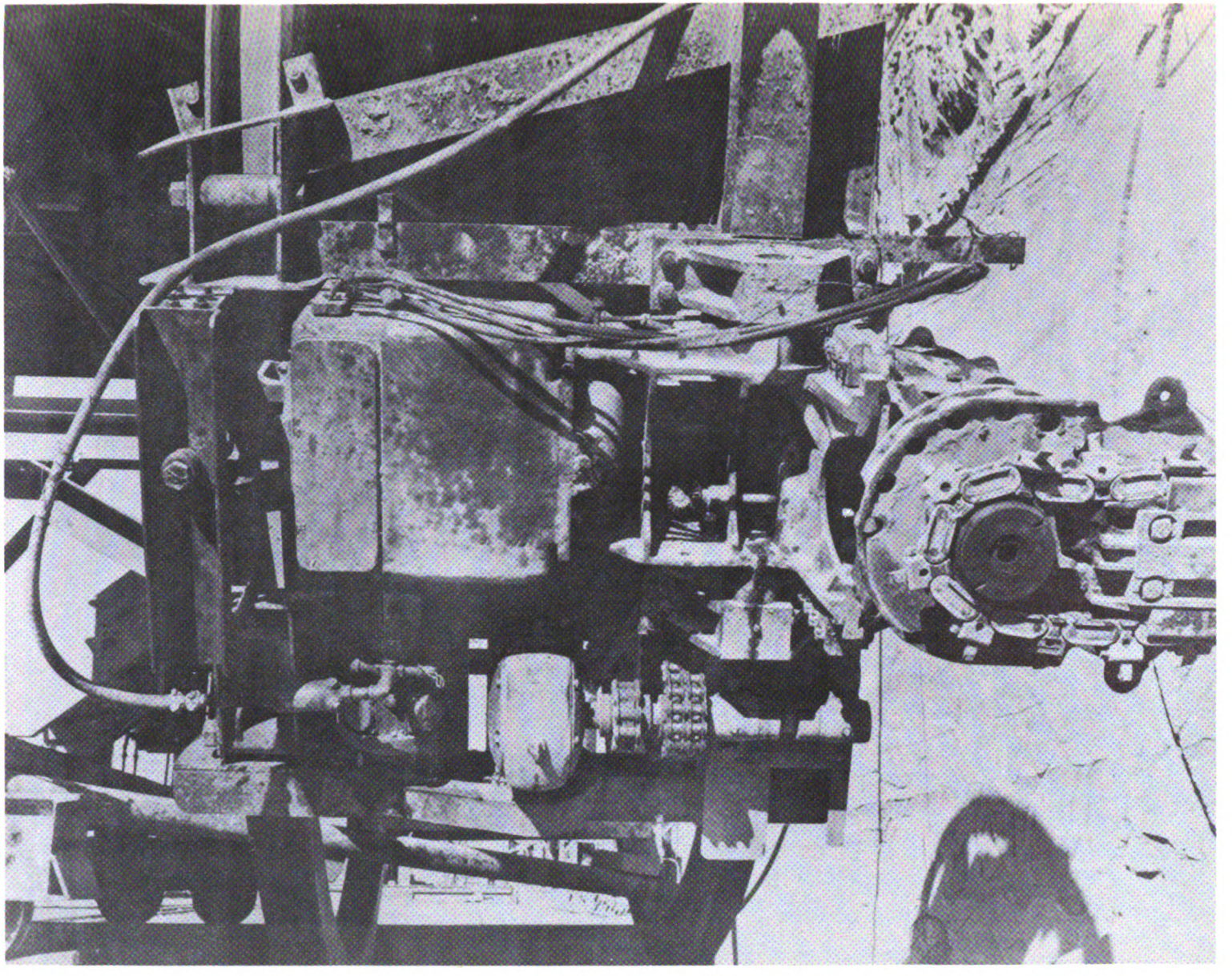

Figure 10. - Side view of carriage and saw. (Covered by Patent Application Serial No. 133583.)

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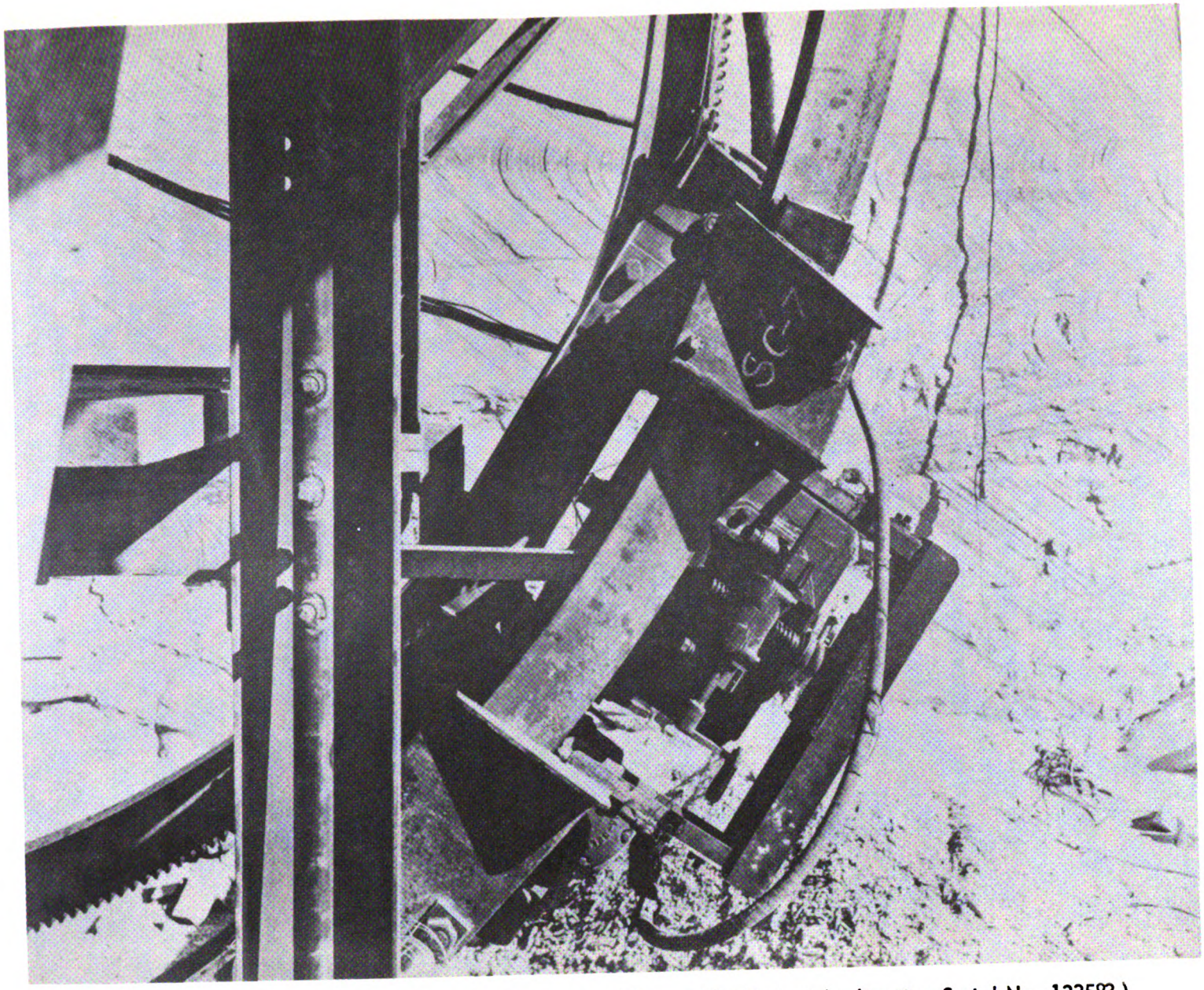

Figure 11. - Operator's view of carriage and saw. (Covered by Patent Application Serial No. 133583.)

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center core. In addition to these two blocks of chalk left at the lower sides, the cut is wedged open with wooden blocks installed approximately every 3 feet across the invert between the two blocks. Figure 9 shows the cut made by peripheral sawing at entry to a tunnel. In this photograph, however, no block of chalk has been left in the lower right corner, and the entire cylinder is supported by wedges and wooden blocks.

The saw makes a 6-inch cut around the periphery of the tunnel. It has little vibration during the cutting operation as it is well braced, not only by the circular ring gear but also by a circular WF-beam mounted back of the circular ring gear. Figures 9 and 10 show such bracing. The carriage advancing on its circular path runs on rollers inside the flanges of the circular WF-beam, and the beam upon which the circular ring gear is attached. In both figures, the circular WF-beam is seen at the left of the picture.

During a complete rotation, the saw is in varying degrees right side up and upside down. As the saw was not designed to operate upside down, the lubrication system for the saw required revision. A force feed system was designed for important bearings, and, in addition, each operator is required to inspect and lubricate the mechanism thoroughly, and rigid inspection is maintained throughout the operating shift.

It is not necessary for the operator to be constantly at the controls while the saw is cutting. If exceptionally hard areas in the rock are encountered, the air motor that drives the carriage will stall without any damage to the electric motor driving the cutting element on the saw. The controls in back of the carriage by the circular WF beam are manipulated easily. To shut off the cutting element of the saw, it is necessary to shut off the 75-hp. electric motor, which is controlled by a push button switch on a long cord. The air motor that drives the carriage is controlled by a valve on the carriage. The direction of the cutter bar is adjusted by a tilting screw in back of the carriage, which will change the angle of the cutter bar either outward or inward. This adjustment enables the operator to adjust the saw if it appears to be binding or running off line. In addition to the tilting screw, the saw blade can be moved radially 15-3/4 inches by means of the screw shown in figure 7. This screw is powered by a small air motor. The operator has no difficulty in following the saw on a circular steel ladder built back of the circular WF beam. Figure 11 shows a veiw of the back of the carriage. The screw that throws the end point of the cutter bar either outward or inward is seen at the lower right of center.

Some difficulty has been experienced with slickensides in the tunnel faces, and although blocks of rock slide out of the sawed cylinder or core along these slickensides and tend to wedge the saw, none have slid out of the walls during cutting of the cylinder. However, blocks have slid out of the walls in localized areas after the solid center core has been blasted.

Tungsten carbide inserts are used for the cutting teeth of the saw. Four to six uses (including the first use) can be made with one set of teeth, and an average of six rounds can be drilled in one use.6/ The company has

6/ A "use" is defined as a bit that has been placed in service, either new or resharpened.

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experimented with various types of inserts and has found that only tungsten carbide is satisfactory for inserts. Cuttings from the saw fall to the floor of the tunnel, but the saw, which starts in the lower right corner, is past the floor portion before these cuttings fill the floor. By the time the full cut is finished, the saw has cut through 16 to 17 cubic yards of solid chalk, and the cuttings from the operation have filled the tunnel approximately one-third the way up the face. The cuttings are somewhat oblong in shape and of various sizes. Table 1 is a screen test on a representative sample of the cuttings.

TABLE 1. - Screen test of cuttings from peripheral sawing

Size	Weight, percent	Weight, percent, cumulative
+ 0.742 inch	10.97	10.97
- 0.742 inch + 0.371 inch	17.76	28.73
- 0.371 inch + 4 mesh	18.13	46.86
- 4 mesh + 6 mesh	10.36	57.22
- 6 mesh + 10 mesh	15.04	72.26
- 10 mesh	27.74	100.00

Analysis of the sample showed 1.84 percent iron and 1.12 percent sulfur. Most of the iron and sulfur is combined in the form of pyrite, which is widely disseminated throughout the chalk formation.

Working parts of the saw and carriage are encased and sealed from dust and saw cutting as much as practical. The circular ring gear is partly covered by a casing attached to the rear of the saw carriage. The casing follows the circuit with the carriage and keeps cuttings from fouling the gear teeth on the circular ring gear. The casing can be seen in figure 6 near the top of the circular ring gear.

The air motor that drives the carriage stalls easily when the saw jams. Its speed is adjustable from 1 inch to 18 inches per minute. The motor is reversible. The electric motor drives the saw by a chain drive to a speed reducer gear. Figure 12 is a side view of the carriage and saw showing the chain drive, encased speed reducer, and enclosed 75-hp. electric motor. The grooved slides over which the head or the cutter bar is retracted are at right of center.

Blast-Hole Drilling

While the saw is advancing around the lower part of the tunnel, blast holes are being drilled; the entire round is usually finished before the saw progresses above the horizontal center line. If blast-hole drilling is not completed before the saw passes above the horizontal center line, the saw is stopped for safety until drilling has been completed. Blast holes are drilled from the movable deck in front of the jumbo with five hand-held, 40-pound, downstroke, rotation jackhammers using solid, twisted, diamond steel having a 1-1/2-inch chisel bit. The drill pattern for both tunnels is shown in figure 13, and order of blasting is indicated by the numbered holes. This

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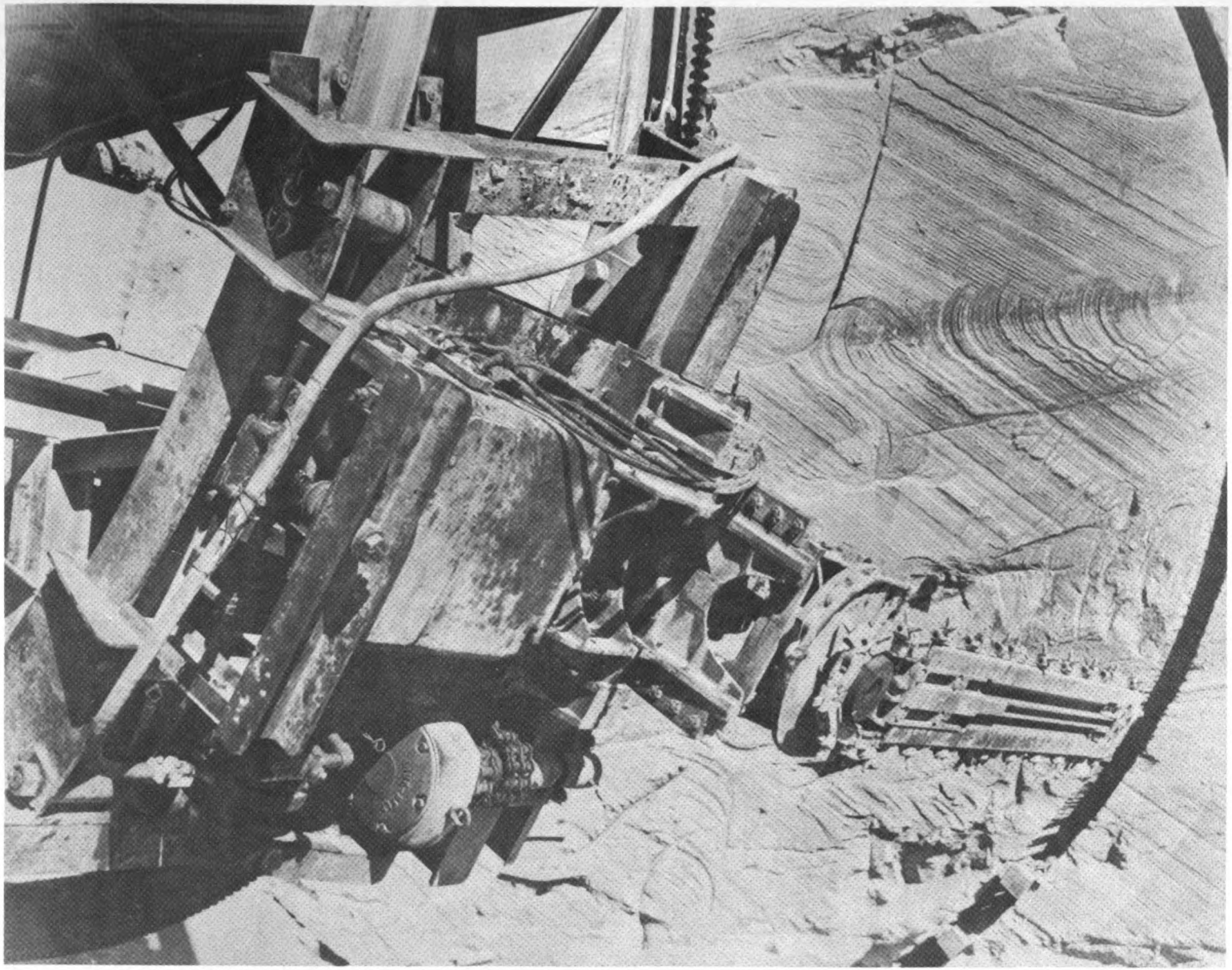

Figure 12. - Side view of the saw carriage. (Covered by Patent Application Serial No. 133583.)

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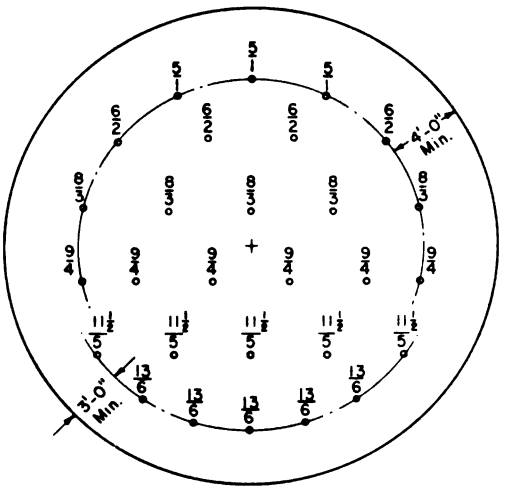
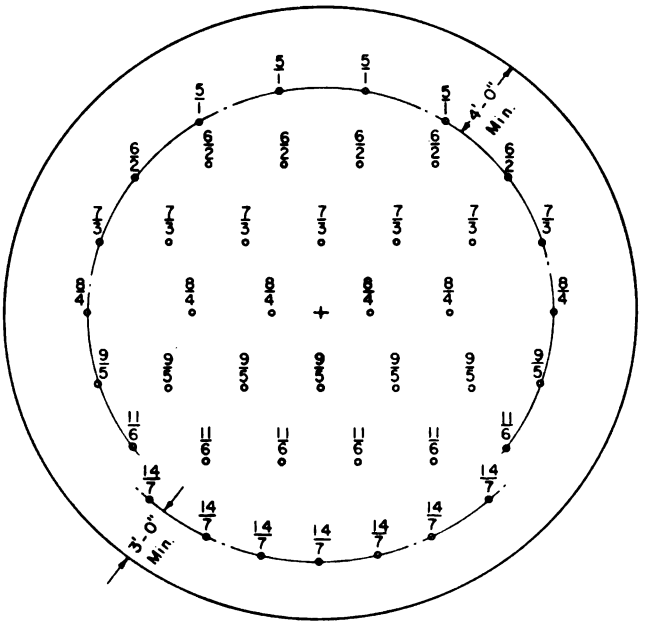


Maximum Loading 100 Lbs.

27-Foot Blasting Pattern



Maximum Loading 150 Lbs.

33-Foot Blasting Pattern

Scale
5 0 5 10 15
Feet

LEGEND

5/1 Number sticks Hercomite 3x
Firing sequence

Minor variations in pattern may be made by drill foreman to avoid seams.

Nov. 1950

Figure 13. - Drill patterns for use with peripheral sawing.

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standard pattern is spotted with paint marks by the shift engineer prior to emplacement of the saw. Minor variations are made in the drill pattern to avoid seams. Normal procedure is to raise the deck with the tugger up to the point where the No. 1 holes can be drilled easily, and the deck is lowered as the holes are drilled in succession downward. The saw cut is used as the free face for blasting; thus, cut holes are not required.

The movable deck upon which the drillers work is made of steel rods so spaced that cuttings and dust will drop through to the floor of the tunnel. The ends of the platform are hinged, and they can be thrown back and laid over the deck to make room for the saw in its circular advance. Figure 5 shows the ends thrown back and lying on the deck of the platform. The jumbo is equipped for arc welding, and while sawing is in progress, the circular ring beams, which have four joints, are arc-welded together. Plates are placed over the joints on both the inside and outside of the beam and welded to the flanges of the ring beams.

Mucking Rock Dust

After sawing and drilling have been completed, the jumbo is moved out of the tunnel by a bulldozer, and a mucking machine is brought in to remove the cuttings. If it is necessary to remove cuttings by hand, a mobile conveyor loading belt is used. The cuttings are shoveled into a hopper, and the belt carries them into a waiting truck. Even when the mucker is used, final cleanup must be by hand to obtain a clean floor so that the steel tunnel-support ring beams may be laid. The final cleanup of the floor of all cuttings prepares the tunnel for the second part in the cycle of operations.

Tunnel Supports

This phase of operation requires the following: (1) Placing the invert segments of the steel ring tunnel support, (2) leveling the invert segment, (3) laying the wooden deck or roadway and the jumbo and mucker rail, (4) placing the arch segments of the steel ring tunnel support, and (5) blasting the round that was drilled during the first part of the cycle.

Circular steel rings on 4-foot centers are used for tunnel support. The complete steel ring is four arch segments. The invert quarter is laid first, followed by the arch three-quarter segment. The beams laid in the large-bore tunnel are 10-inch WF, 33-pound; 8-inch WF, 24-pound beams are used in the small-bore tunnel. The steel ring tunnel supports are brought into the tunnel and placed in position by a truck jumbo.7/ The jumbo consists of a truck mounted with an A-frame, upon which a platform moves up and down on the vertical face. The platform is moved by a hoist, which is energized by a power take-off from the truck motor. Cables leading from the hoist through pulleys mounted on both the top and bottom cross beams

7/ Truck jumbo designed by R. B. Jewell, Resident Manager, and Geo. L. Lyle, General Superintendent, Silas Mason Co., Fort Randall Reservoir project, Pickstown, S. Dak.

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of the A-frame serve to move the platform either up or down. The truck jumbo backs into the tunnel to place the tunnel-support steel in position. Figure 14 shows the truck jumbo carrying a steel arch segment. The segments are placed on the platform by the crane seen in the background.

Placing the Steel Invert Segments

The invert segment, which is the bottom quarter segment of the steel ring, is brought in by the truck jumbo hanging from a cable. Usually, two sets are brought into the tunnel, joined by 4-foot collar braces; however, if there is room to leave 14 feet between the steel and tunnel face after blasting, three are placed at once. The truck jumbo is backed into position, and the segments are lowered to the floor of the tunnel and set to line and grade. Wedging and blocking are almost uniform along the invert because of the smooth wall resulting from sawing the periphery. The first operation of the second part of the cycle is finished when the jumbo releases the two or three invert segments and leaves the tunnel to pick up an arch three-quarter segment.

Leveling the Invert Segment

The invert segments are bent to exact roundness, and at the work shop steel brackets are bolted to the segment on each end in such a manner that the top face lies horizontal. These brackets are set at exact distances from each end of the segment with a gage and bolted fast. Figure 5 shows the brackets bolted to each end of the invert. The invert segment is set to line and grade with wedges and blocks by leveling from the brackets. Horizontal distance between segments is maintained by 4-foot spacer bars or collar braces.

Laying the Wooden Deck and Track

When the jumbo truck leaves the tunnel to pick up the hinged ring arch segments, another truck brings in timber and rail. The timber, cut to exact dimensions, is used for constructing a plank roadway or timber deck. First, timber beams rounded on one side and flat on the other are laid, rounded side down, on the leveled invert segments, and then 4- by 12-inch planking is laid on the horizontal surface. Rail for the mucker also is laid on the horizontal timber beams between the planking. The planking is laid up to the steel brackets, which are bolted upon the ends of the inverted segments. Six- by 12-inch wooden timbers are laid on the steel brackets, and upon these the jumbo rail is laid exactly in the center of the timbers. As the inverts have been leveled and set to line and grade from the steel brackets, the adding of 6-inch thick timber places the jumbo rail in leveled position for the drill jumbo, which was designed to be concentric with the tunnel when resting on these rails. Figure 5 shows the jumbo rail resting upon the 6- by 12-inch timber and the timber resting upon the bracket bolted to the invert.

Placing the Steel Arch Segment

When the timber truck withdraws, the truck jumbo re-enters, backing slowly into position with the three upper arch segments, connected with

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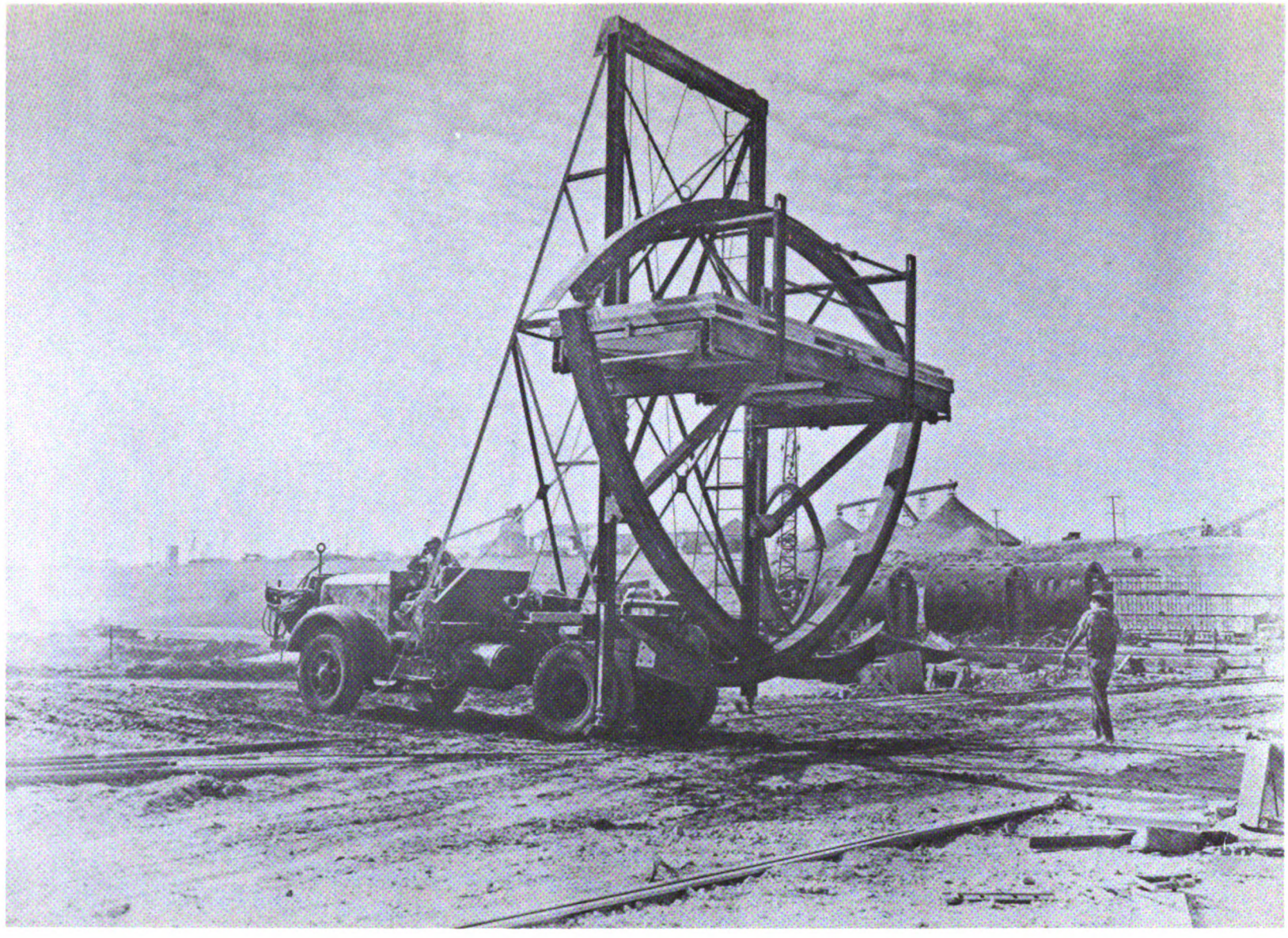

Figure 14. - Truck jumbo carrying a hinged steel arch segment ready to back into a tunnel.

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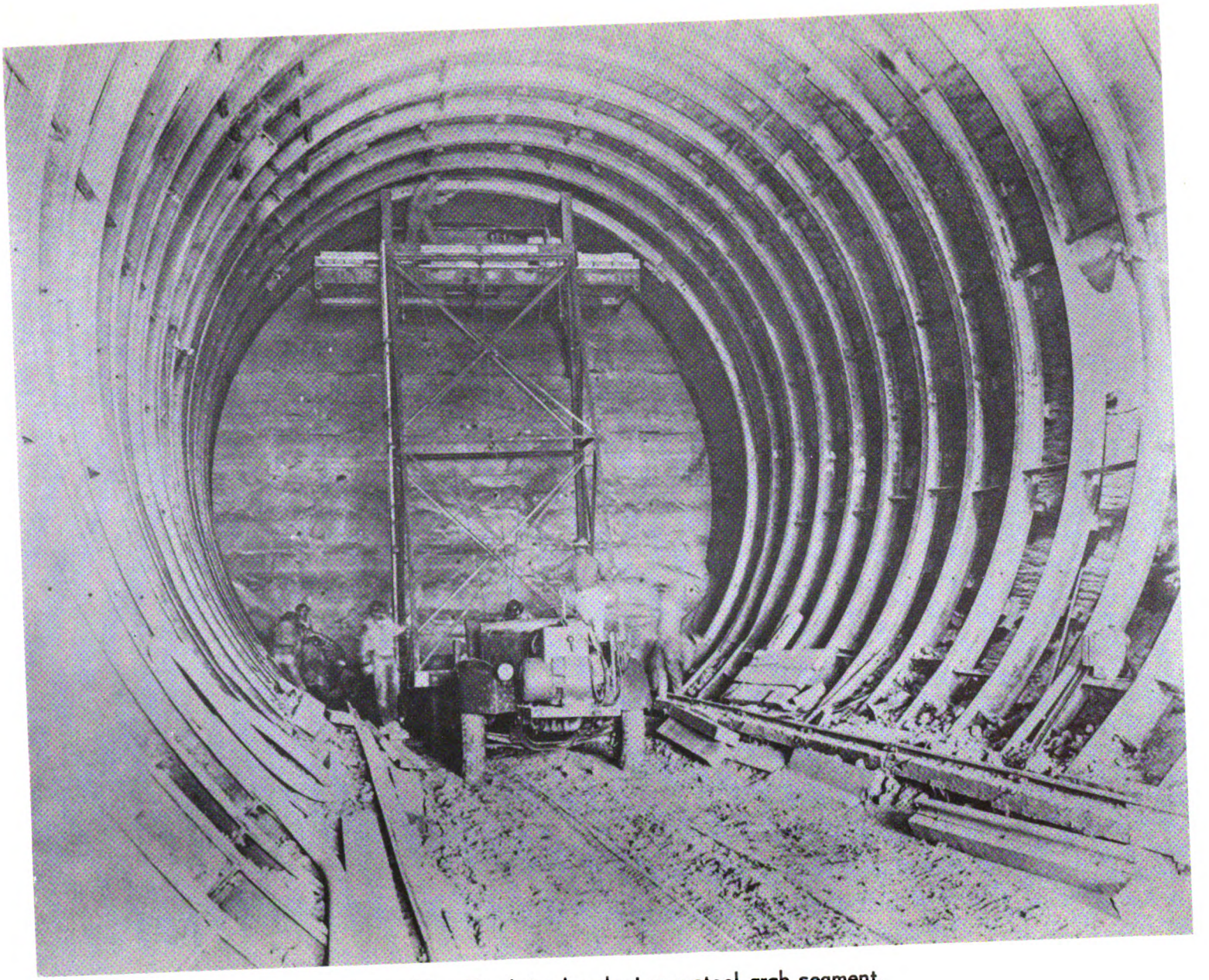

Figure 15. - Truck jumbo placing a steel arch segment.

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temporary hinges, resting on its movable platform. Figure 14 shows the truck jumbo about to back into a tunnel. Only one arch ring can be carried at a time by the truck jumbo. The top quarter segment of the arch lies across the steel rails of the platform with the two side quarters attached to the top quarter by hinges. They are held in crossed position by a temporary bolt.

The hinges that connect the quarter segments are made of girder flange angles. Two legs of the girder flange angle are bent into a complete hook and fit over the flanges of the circular ring beam, and the other two legs are bolted together. This forms a clamp that is kept from slipping on the ring beam by the butt plate at the segment joint.

To install the arch segment, the loaded truck jumbo is backed over the newly constructed wooden deck into position, and the platform is raised by means of the hoist until the ring beam is against the crown of the tunnel. The temporary bolt is removed, and the arch segments hanging free on the hinges are then opened into place. Figure 15 shows the truck jumbo placing a steel arch segment. The butt plate of the arch segment is joined against the butt plate of the invert segment. Four-foot spreader angles provide proper horizontal distance. As the arch segment is made to proper size, it must, of necessity, fall into its proper position, because it rests upon the leveled invert segment. The arch segment is wedged down around the full perimeter and bolted at the four joints. The smooth walls and back of the tunnel allow the segment to be set and wedged into position easily. Hinges are removed and used for the transportation of other arch rings. The truck jumbo then goes after the second arch ring, which is installed in the same manner as the first. The number of arch rings placed correspond to the invert segments placed.

Loading and Blasting the Round

When the tunnel supports have been solidly blocked, the round drilled in the first part of the cycle of operations is loaded and blasted. Figure 13 shows the drill pattern and order of blasting.

The 6-inch ring cut by the saw is used as the free face for blasting. Explosive cartridges are 1-1/4 by 8 inches. Table 2 shows the explosives required to break an average round in the large bore section after peripheral sawing.

TABLE 2. - Explosives required to break an average round in the large bore section after peripheral sawing

Holes	Number of holes	Sticks of powder per hole	Total sticks of powder
1	4	5	20
2	6	6	36
3	7	7	49
4	6	8	48
5	7	9	63
6	6	11	66
7	7	14	98
	43		380

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Blast holes are loaded progressively heavier from the top of the tunnel downward; the lower No. 7 holes are loaded with almost three times as much explosive as the No. 1 holes. R. B. Jewell reports that loading, such as shown in figure 13, results in the steepest possible muck pile and excellent fragmentation of the chalk. There is little chance of the round varying from the standard pattern, as the holes are spotted by the shift engineer. The maximum loading in the large bore tunnel is 150 pounds of powder and 100 pounds of powder in the small bore section. The explosive factor in both tunnels is 0.6 pound per cubic yard of solid chalk.

The truck jumbo is used in loading. The normal procedure is to cut off all electric power within an area extending back 100 feet from the tunnel face. A string of electric lights is hung across the portal to serve as warning that explosives are in the tunnel. The truck jumbo backs into the face, and the holes are loaded from the movable platform.

The face is illuminated during loading by two special, sealed-beam, 100-watt, 6-volt floodlights powered from a regular 6-volt automobile battery. The battery is set in a steel case and well insulated, so that there is no danger of the case being energized.

Paper tamping bags filled with sand are used for stemming. Wood safety primers only are employed, as recommended by U. S. Bureau of Mines Bulletin 439.[8/] The round is detonated electrically, and exceptional safety measures are taken during loading and during the firing period. In addition to shutting off electric power 100 feet back from the face and stringing lights across the portal, a set procedure is followed by the blaster when the round is fired.

A permanent firing line is advanced with the tunnel, but never closer to the face of the tunnel than 100 feet. The permanent line is hung from the steel ring beams by means of insulators on the side of the tunnel nearest the river. All other electrical wiring is hung on the opposite side, farthest from the river.

Delay electric blasting caps equipped with 16-foot leg wires are connected in parallel across a pair of bare No. 4 copper bus wires. The leg wires are connected singly to the bus wires, which are hung on wooden pegs across the face. The bus wires are shunted before attaching the leg wires. The bus wires are connected to the permanent firing line by No. 14 rubber-covered single-conductor wire. Split bolt connectors are used to connect to the permanent firing line.

After all connections have been made at the face, the shunt wire in the bus lines is cut; this then places the shunt back to a closed firing switch, which terminates the permanent firing line at the portal of the tunnel. There are two double-throw safety switches at the portal. The first is a power switch; the second is a firing switch, which energizes the permanent

8/ Harrington, D., and Ash, S. H., Some Essential Safety Factors in Tunneling: U. S. Bureau of Mines Bull. 439, 1941, pp. 37-41.

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firing line. The permanent firing line is two separate strands of single-conductor No. 6 cable.

Both switches at the portal are always kept locked in their shunt position and well separated; 440-volt, single-phase, 60-cycle A.C. is brought to the upper terminals of the power switch. The switch is shunted and, of course, locked in this position. Connected to the midpoint take-off is a small step-down transformer, which is used in conjunction with a siren; and also a take-off with a 25-foot, two-conductor, No. 6 cable, which terminates in a female two-conductor plug. This plug connects to a male plug. This cable with the male plug is attached to the upper terminals of the firing switch, which also is locked in shunt position on the lower terminals. The permanent firing line takes off from the midpoint.

After all connections are made at the face and the bus shunt wire is cut, the procedure at the portal is as follows:

1. The power switch is unlocked and thrown off shunt position to power.

a. This energizes the female plug and starts the warning siren. The siren is connected to the transformer, which steps down the 440 volts to 110 volts.

2. The female plug is connected to the male plug, which immediately brings the power to the upper terminals of the firing switch.

3. The firing switch is unlocked and thrown to power.

When the last step in the procedure is accomplished, the round is detonated. The firing switch is then locked in shunt position, the plugs disconnected, and the power switch thrown in shunt position, which immediately shuts off the siren. The string of lights is taken from across the portal, and the ventilation fans are turned on.

This procedure of detonating the tunnel round has been worked out by D. S. Waddy, Jr., electrical superintendent, Silas Mason Co. The main principle behind the entire procedure is safety. At no time can the blaster hurry the procedure, and each step must be taken deliberately and in sequence. When the blaster throws the power switch, the siren immediately gives warning that a round is to be fired. The blaster must then walk to the firing switch, insert the plug, and throw the switch before the round is blasted. The siren keeps sounding until the power switch is back in shunt position.

Mucking

After the ventilation fans have cleared the tunnel of gases, the face of the tunnel is scaled of loose rock. Usually, the crown and walls do not require scaling, because the saw leaves a smooth surface with no loose fragments.

Mucking is done with a Conway mucker, which is a belt-loader type driven by a 100-hp. electric motor with a separate 30-hp. motor driving the belt.

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The broken rock slides out of the back of the dipper and down the bottom onto a conveyor, which discharges into a 15-ton truck at the rear. The truck is equipped with a special hitch and coupled to the mucker by an adjustable draw bar extending from the mucker. Both truck and mucker operate as a unit, the truck assisting the mucker in crowding the muck pile. Figure 16 shows the mucker in operation.

The adjustable draw bar has two positions at which the belt loader loads onto the truck. In one position, when the truck is backed well under the loader and hitched to the mucker with the short adjustment on the draw bar, the rock is loaded in the front end of the truck bed. Later, the draw bar adjustment pin is pulled, the truck moves forward, and the pin is dropped at the long adjustment on the draw bar. Then, the belt loads the rear end of the bed. The truck is kept in reverse gear and assists the mucking machine in crowding the muck pile at a signal from the mucker cable tender. When the operator retracts the mucker from the pile, the driver disengages the clutch, and the mucker moves back under its own power. Figure 16 shows the truck hitched at the long adjustment on the draw bar, with the mucker cable tender signaling the truck operator to disengage the clutch.

A 10-cubic yard truck is loaded in 3 to 5 minutes. As soon as it is loaded, it is unhitched and moved out of the tunnel. Then, another truck backs in to be loaded, and the operation is repeated. In addition to the actual loading time, considerable time is consumed in waiting for the loaded truck to get out of the tunnel and the empty to back in.

The Conway mucker operates on rail, whereas the truck runs on the timber deck or roadway. The mucker has little side clearing to do, because the rock continues to roll toward the center of the tunnel as the muck pile diminishes.

Boulders as large as 3 feet in diameter are picked up by the mucker and transferred to the truck. Scaling the face of the tunnel continues while mucking is in progress. In the period during which a loaded truck is leaving the tunnel and another is waiting to back in to be loaded, rock is loaded on the conveyor belt, which has been stopped. When the truck is hitched, the belt is started, and the rock lying on the belt is transferred to the truck. This procedure tends to speed loading and shorten mucking time. Figure 17 shows a truck assisting the mucker in crowding the muck pile.

Final cleanup is made by hand so that no muck will be left on the floor to interfere with peripheral sawing, which once again starts the complete cycle of operations.

TUNNEL EXCAVATION BY PERIPHERAL DRILLING

Tunnel excavation by peripheral sawing is a comparatively recent practice at Fort Randall. Initially, two of the tunnels were advanced by line drilling or peripheral drilling 5-inch-diameter holes on 10-inch centers outside the circumference margins of the tunnels.

The peripheral drilling at a rate of 4 feet per minute was done with eight No. 580 Chicago pneumatic electric coal augers mounted on the circumference of a ring built on a jumbo. About 120 holes 8 to 9 feet deep were

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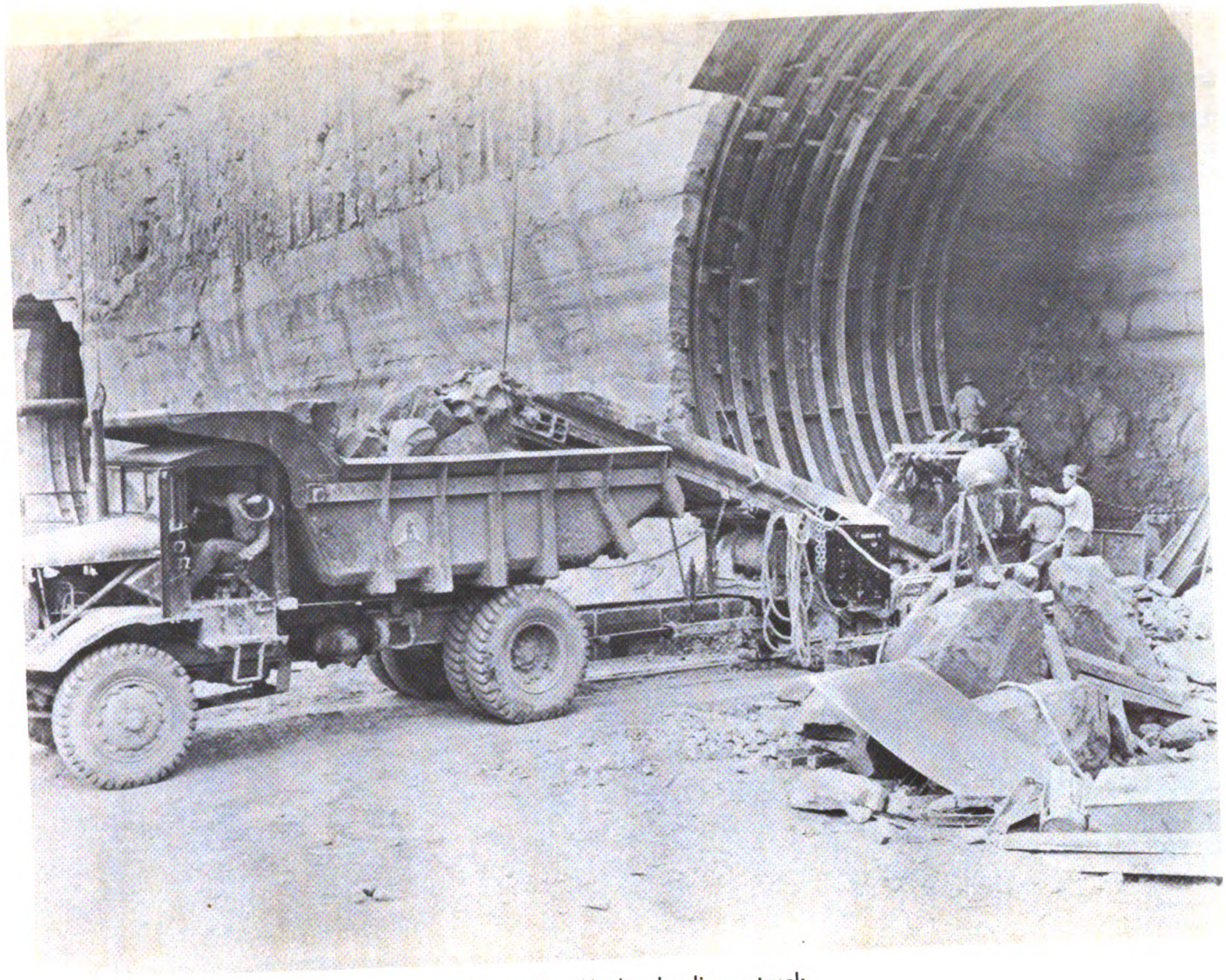

Figure 16. - Mucker loading a truck.

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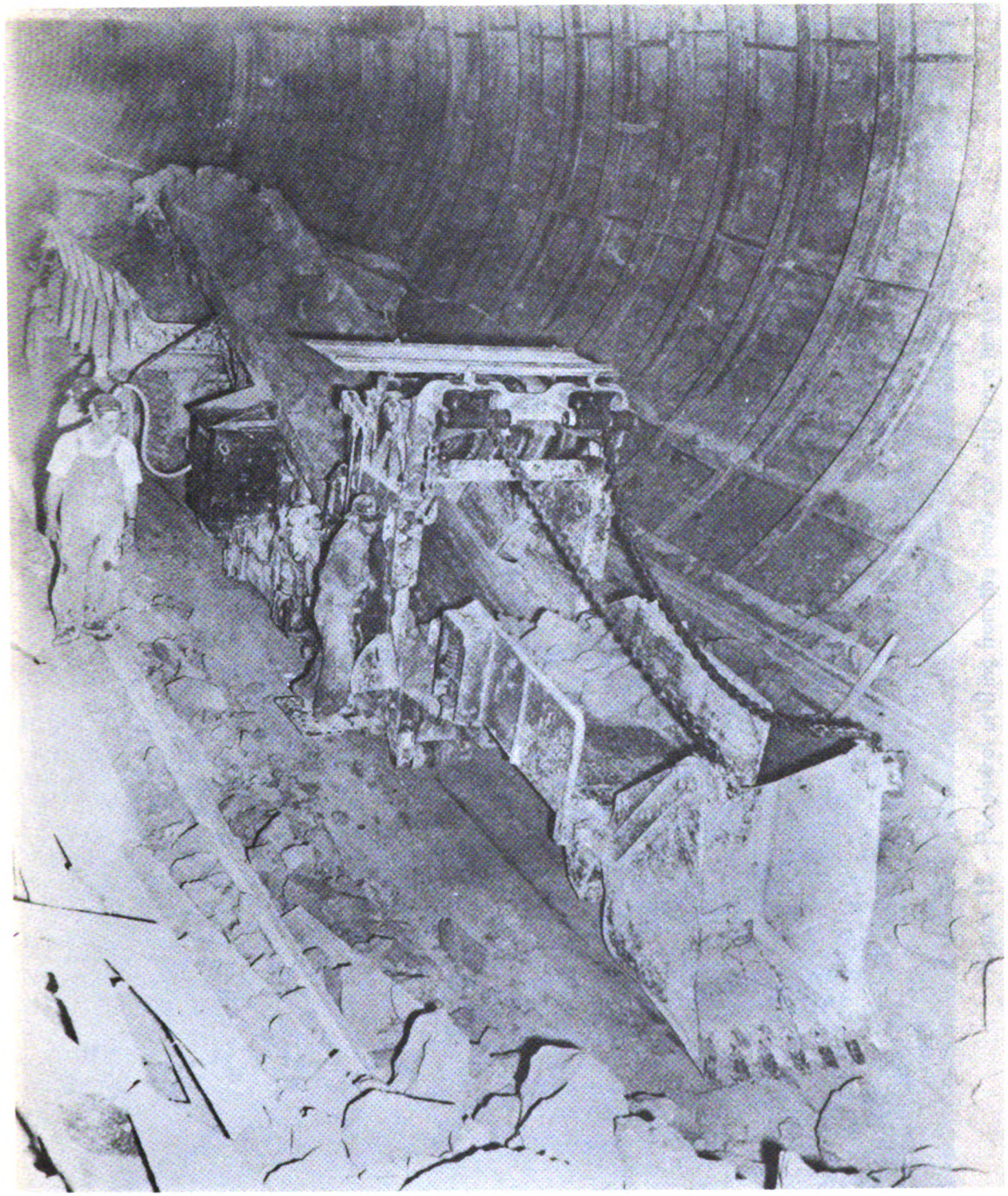

Figure 17. - Mucker crowding the muck pile.

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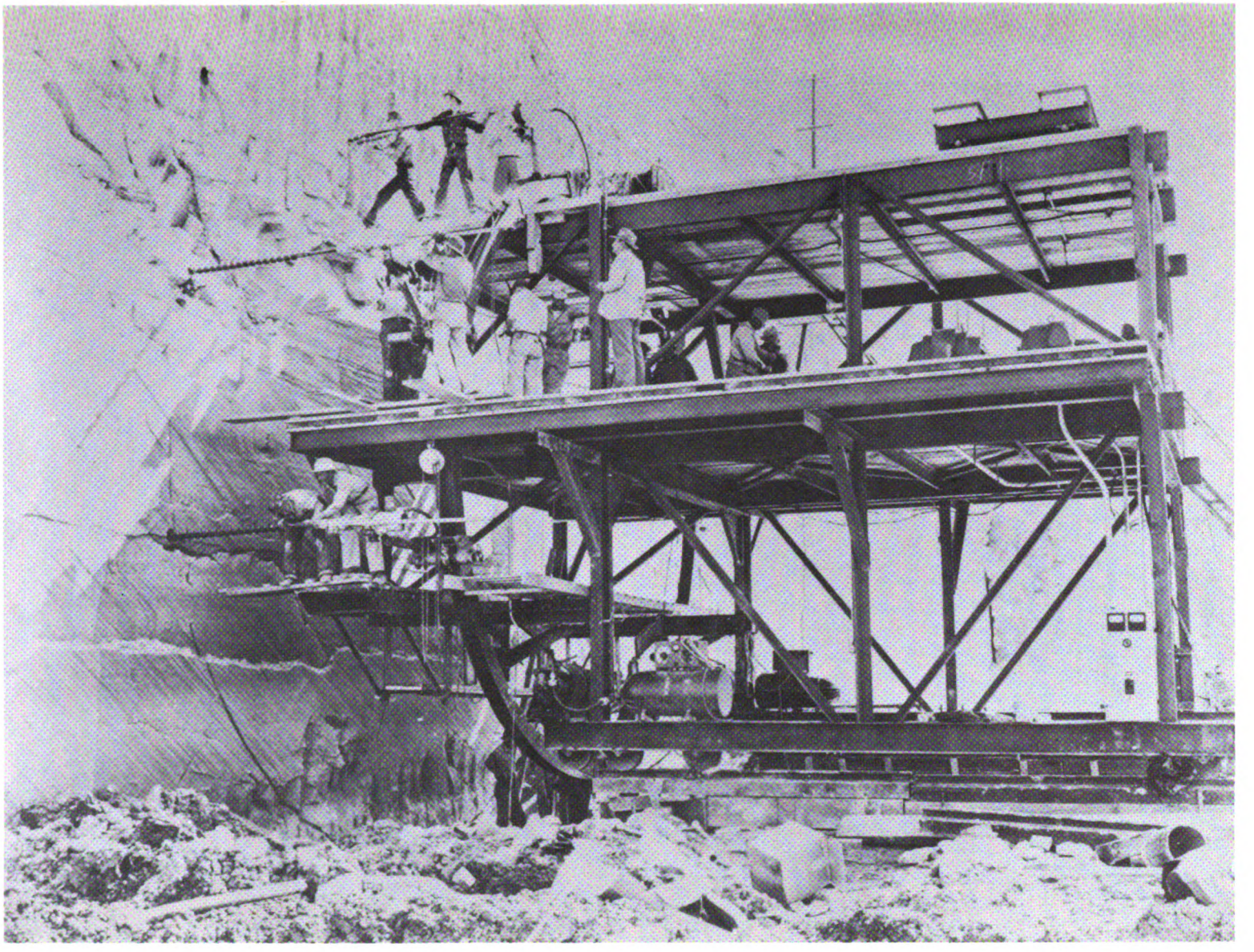

Figure 18. - Peripheral drilling from the jumbo at entry to a tunnel.

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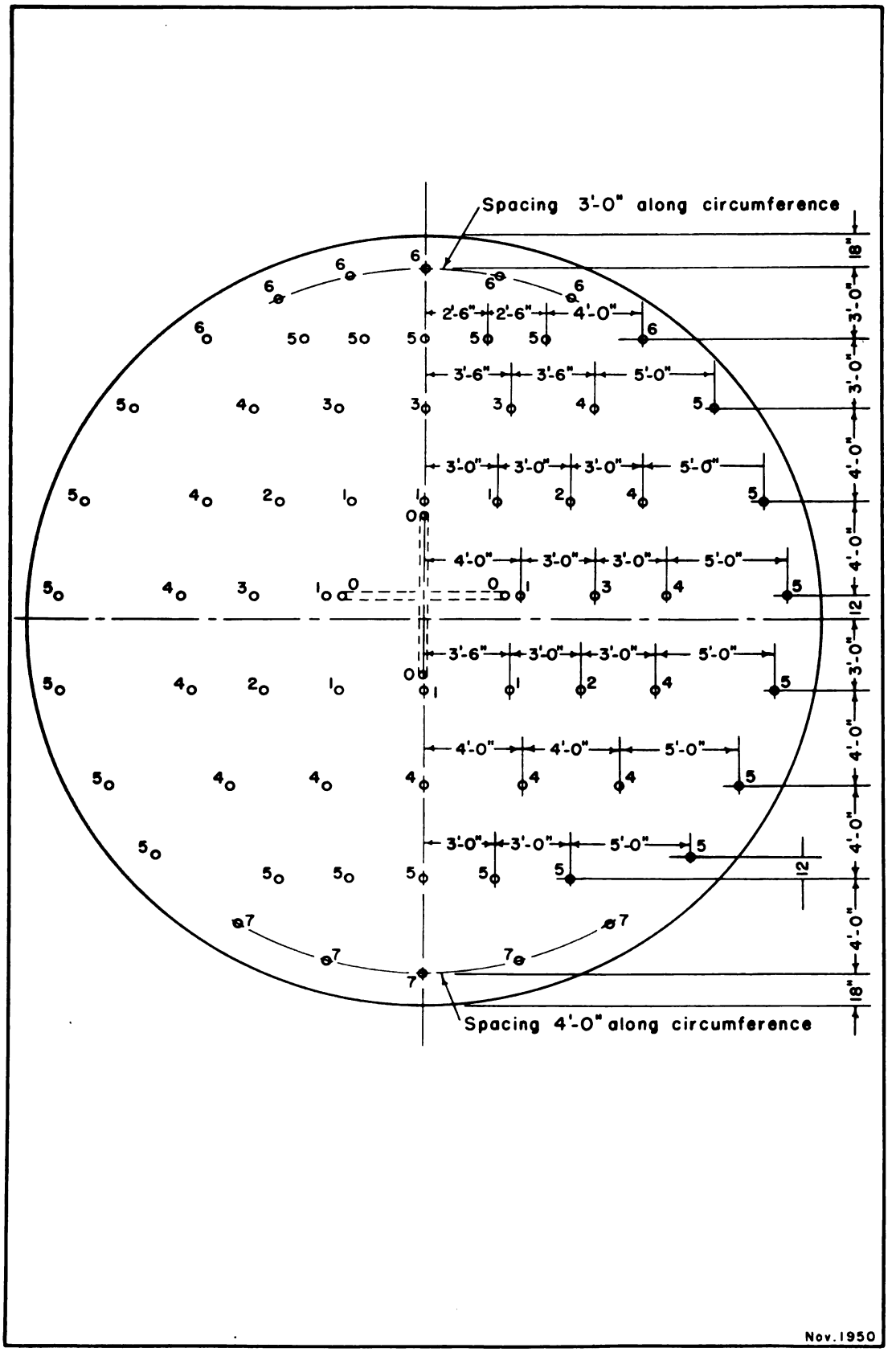

Figure 19. - Drill pattern for use with peripheral drilling.

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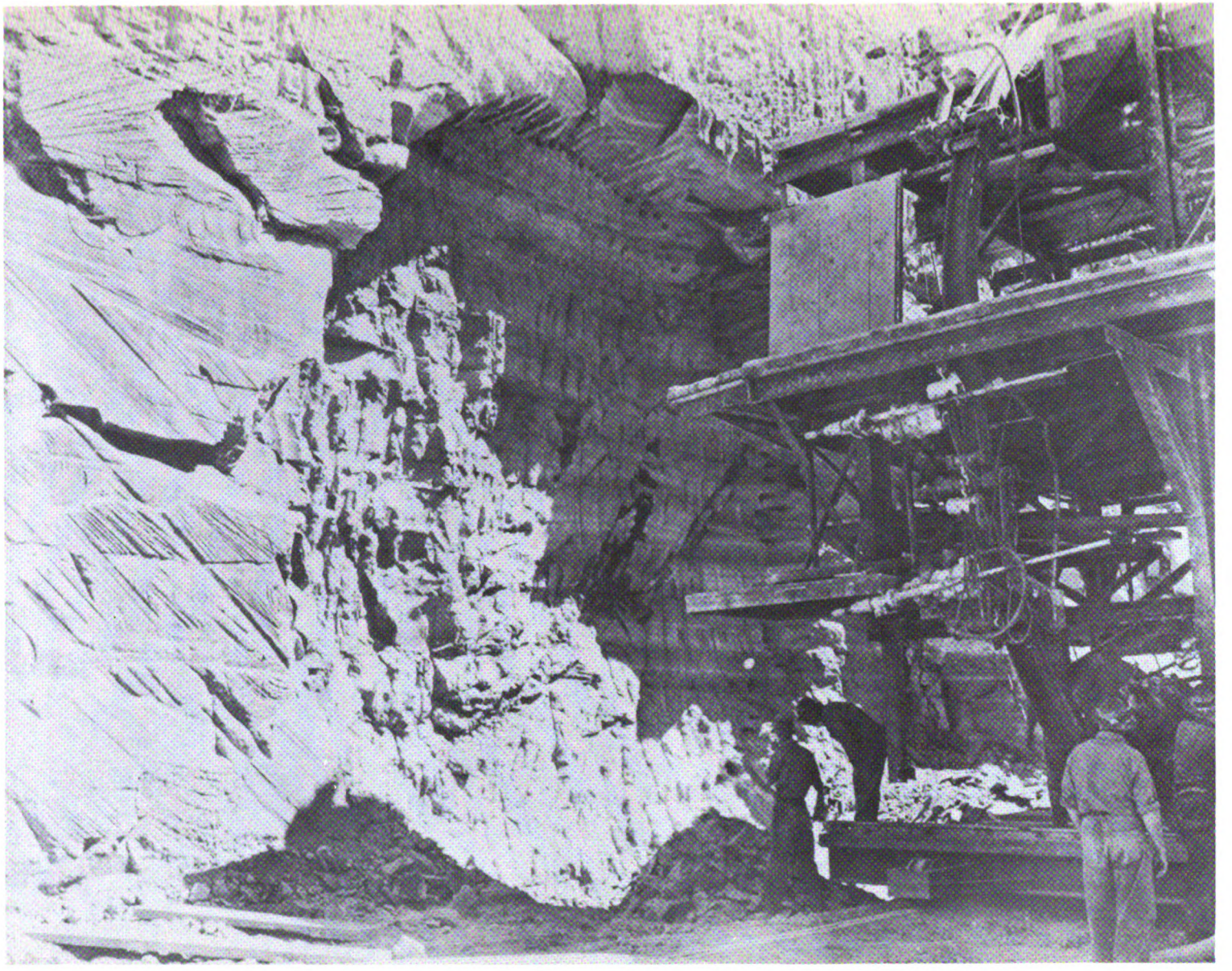

Figure 20. - View of a cut made by peripheral drilling followed by blasting.

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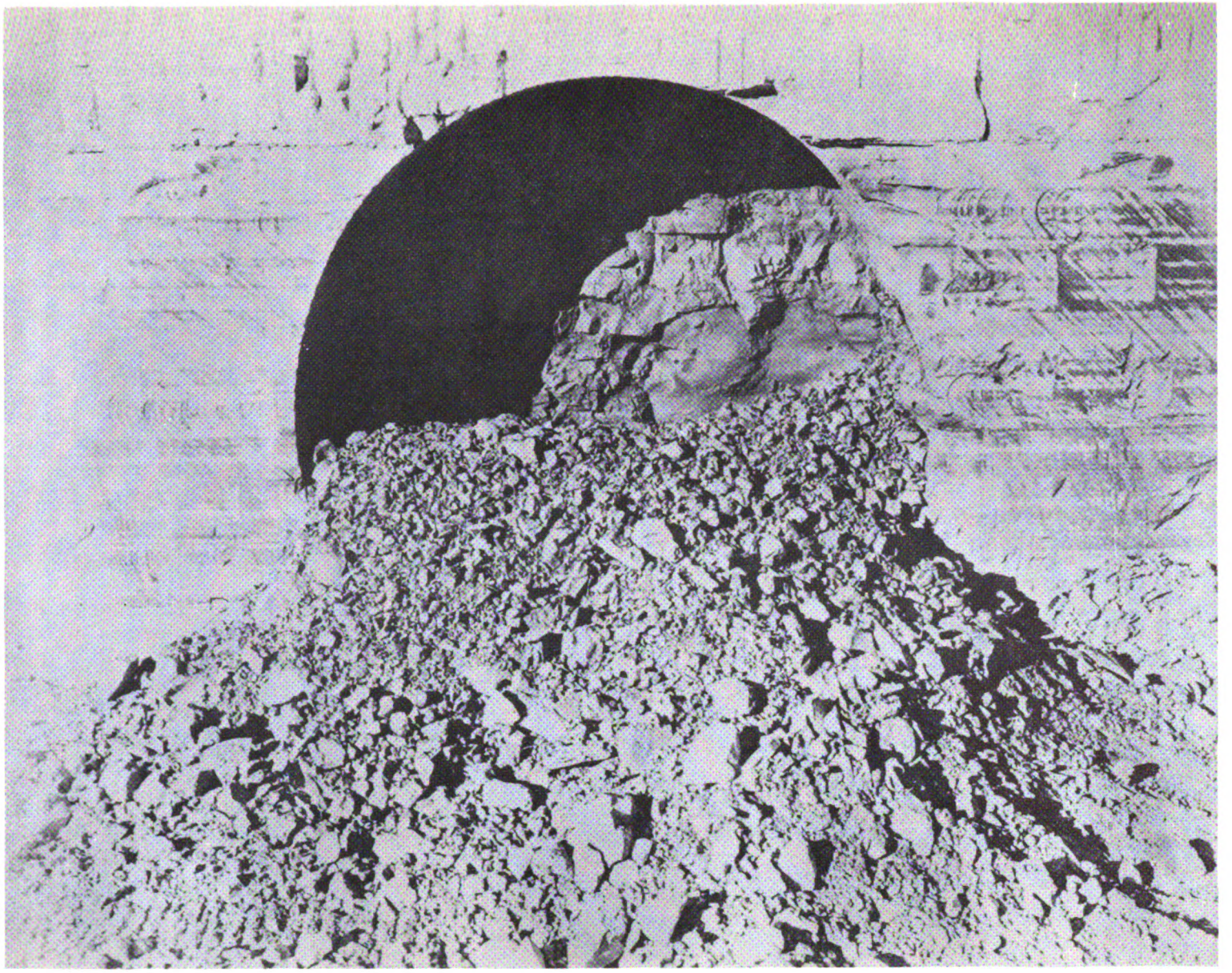

Figure 21. - View of cut made by peripheral sawing followed by blasting.

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drilled around the periphery of the tunnels. Figure 18 shows peripheral drilling from the jumbo at the start of a tunnel entry.

Blast holes were drilled in the manner used for peripheral sawing, but on a drill pattern and firing order as shown in figure 19. The drill pattern is essentially a diamond cut with the No. 0 holes angled toward the center, and the other holes are drilled straight. The explosive factor was 0.9 pound per cubic yard of solid chalk. The rotation of firing broke the chalk toward the free face of the cut, but the outside holes also broke to the peripheral drilled holes.

COMPARISON OF PERIPHERAL DRILLING AND PERIPHERAL SAWING METHODS

R. B. Jewell reports that peripheral sawing eliminates the rough surfaces that usually result from peripheral drilling, thereby facilitating installation of steel supports in the tunnel. It also eliminates, to a large extent, fracturing of the tunnel walls, which usually follow peripheral drilling and blasting because there is always a certain danger that blocks might be loosened from the tunnels as the outside holes break to the peripheral drilled holes. Figure 20 is a view of a cut made by peripheral drilling followed by blasting; for comparison, figures 15, 16, and 21 show cuts made by peripheral sawing followed by blasting. As is noted in figure 15, the steel supports are easily placed and wedged against the smooth rock.

The peripheral sawing and blasting method uses less powder, and fewer blast holes need be drilled to break the round. In an average round in the large bore section, the line-drilling method required 68 blast holes and approximately 120 5-inch-diameter periphery holes on the circumference margin of the tunnel, whereas the periphery sawing method requires 43 blast holes and the 6-inch cut by the saw on the circumference of the tunnel. Time is saved in drilling fewer blast holes, and, also, blast-hole drilling and sawing can be done simultaneously. In addition, the explosive factor was reduced from 0.9 pound per cubic yard solid in line-drilling to 0.6 pound per cubic yard solid in peripheral sawing.

Peripheral sawing has reduced the time consumed in every part of the cycle of operations under that required by the peripheral drilling method. In part one of the cycle, the method has speeded drilling the blast holes and ringing the circumference. In part two, the tunnel-support steel is easier to place in the tunnel, and the steel is easier to level into position by wedging against the smooth wall rock. In addition, the smaller number of blast holes are more quickly loaded. Mucking, which is part three of the cycle, is done more quickly by the sawing method than by the drilling method because (1) usually no time is required to scale down the crown and walls, (2) there is less throw of the muck and consequently less cleanup, and (3) the standard drilling pattern with the saw yields better fragmentation and the steepest possible muck pile. The excellent fragmentation and steep muck pile are illustrated in figure 21.

The peripheral sawing method also has contributed towards a substantial reduction in costs because there is no overbreak. The tunnel can be excavated to exact dimensions, with resultant saving in concrete.

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Time Required For Cycle Of Operations

The speed and time of a complete cycle of operations depend on many factors. Line drilling required a longer time to complete a cycle than did the peripheral sawing method.

Table 3 shows the weekly and daily average advance from May 31, 1949, to September 16, 1950. Each work week is shown in the table with the corresponding number of working days and the number of rounds per week; the number of tunnels under construction in any one week is shown in the first column. The weekly and daily average advance as well as the cumulative weekly advance, also are shown. The average daily advance was 26 feet, and the average weekly advance was 154 feet. The average feet per round was 8.2. The weekly advance varies considerably from the average, reaching the peak of 311 feet in the week of January 16 through January 21, 1950.

Figure 22 is a graph with the weeks plotted as the ordinate and the feet advanced each week as the abcissa. The flatter the curve, the greater the advance each week. The greatest advance was made during the period when three tunnels were under construction and when peripheral sawing was employed. In the curve where three tunnels were under construction, the curve levels off slightly, indicating a speed-up of advance. For this reason, three tunnels were kept under construction whenever it was possible.

For comparison of the line-drilling and peripheral sawing methods, four places were selected in the curve where charts of typical cycles could be made. The locations of these typical cycles are shown in figure 22. The charts of the typical cycles are shown in figures 23, 24, 25, and 26.

Figures 23, 24, 25, and 26 are bar graphs with the length of each bar designating the length of time required for any one part of the cycle of operations. Legends on the figures denote the type of operations. The weekly period can be compared with the same period in table 3 to obtain the average daily advance and weekly advance. Open bars within the graphs denote major machinery breakdowns that halted operations over the open period. Open spaces between the bars are periods of lost time, which include moving line-drilling or saw jumbos out of the tunnels, traffic conjestion on the lower roadway, derailed equipment, or many other incidents that can occur in an operation of this size. The length of the bars for the mucking time includes the wait time for loaded trucks to move out and empty trucks to move into the tunnels. The length of the tunnel will affect the time required for mucking. The graphs were drawn from daily shift reports, and some of the time included within the bars may be lost time that was not explained on the shift report.

The detailed procedure on each part of the cycle of operations has been explained. For convenience, the cycle time is taken from load and blast to the next load and blast, and in every graph the load and blast period has been made solid black.

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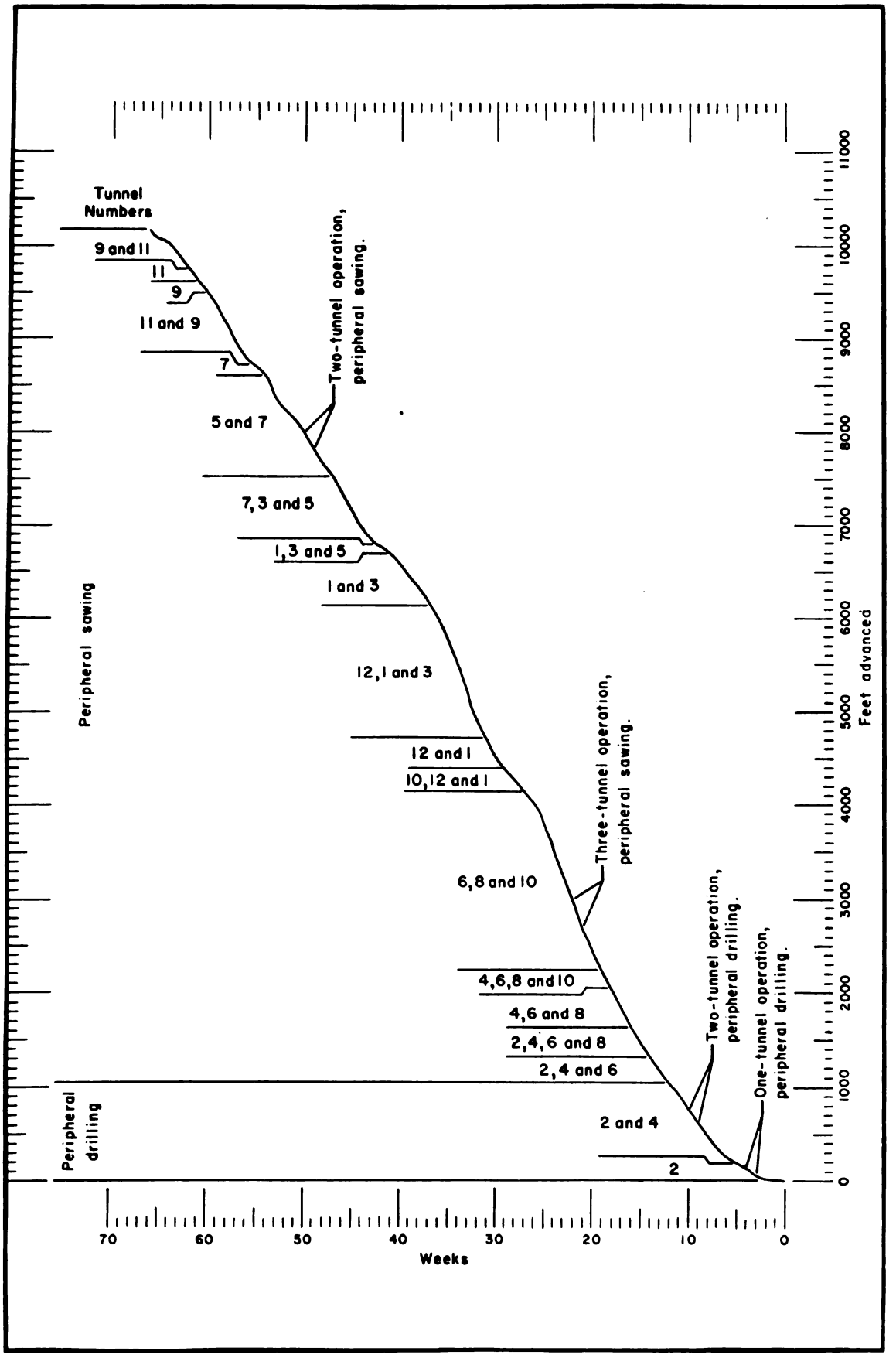

Figure 22 - Graph of feet advanced each week.

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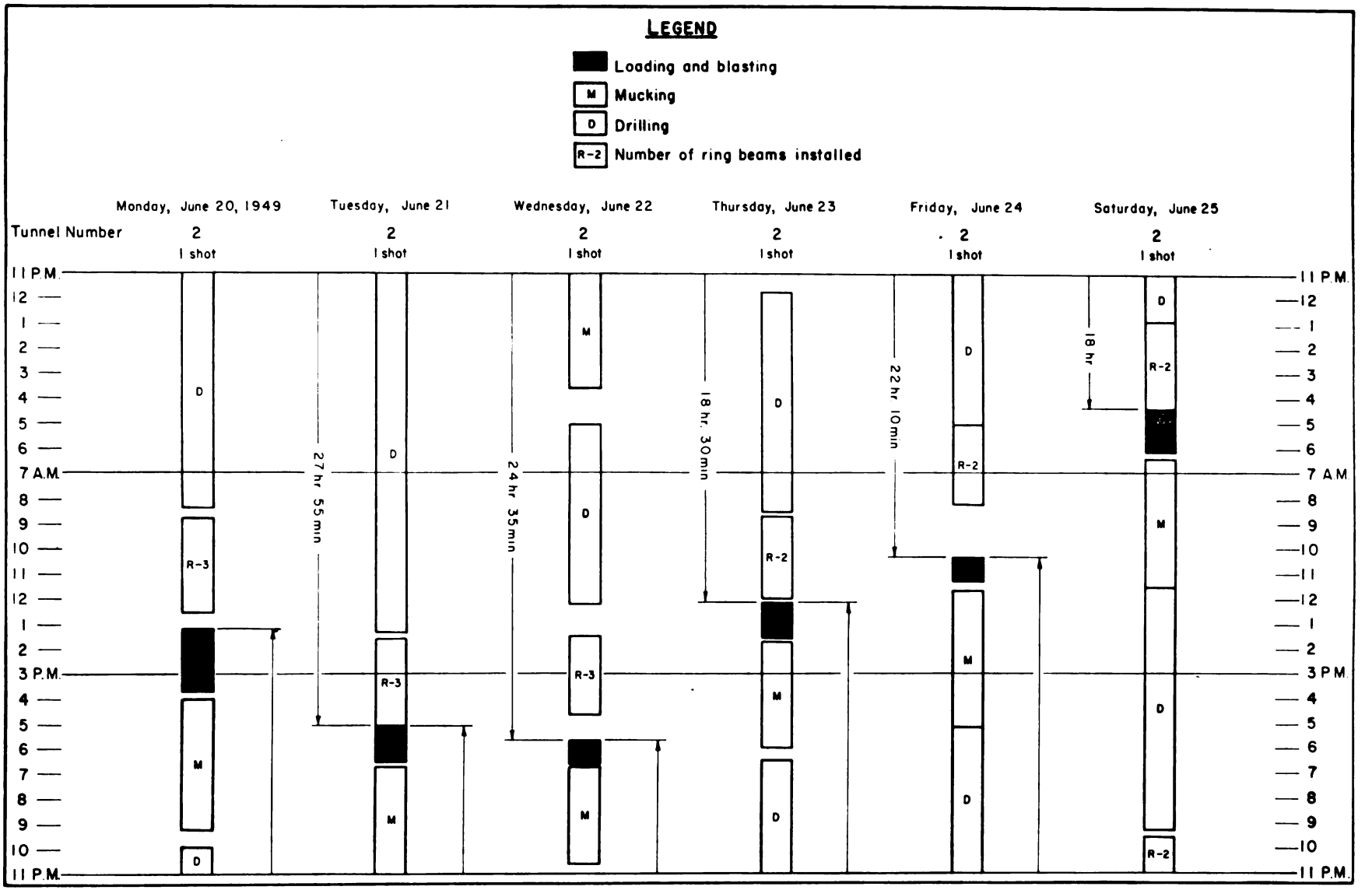

Figure 23. - Typical cycles for one-tunnel operation, peripheral drilling.

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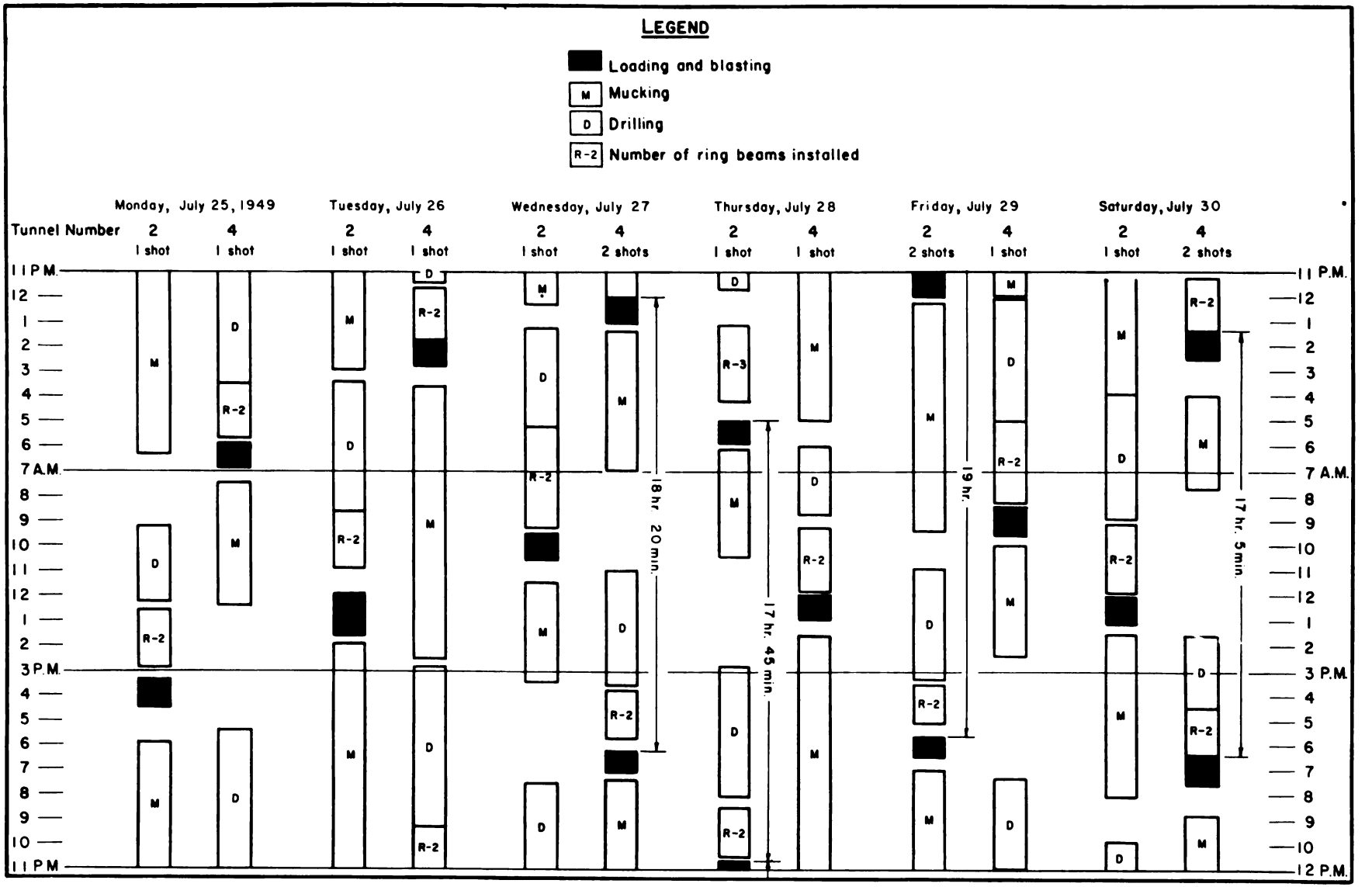

Figure 24. - Typical cycles for two-tunnel operation, peripheral drilling.

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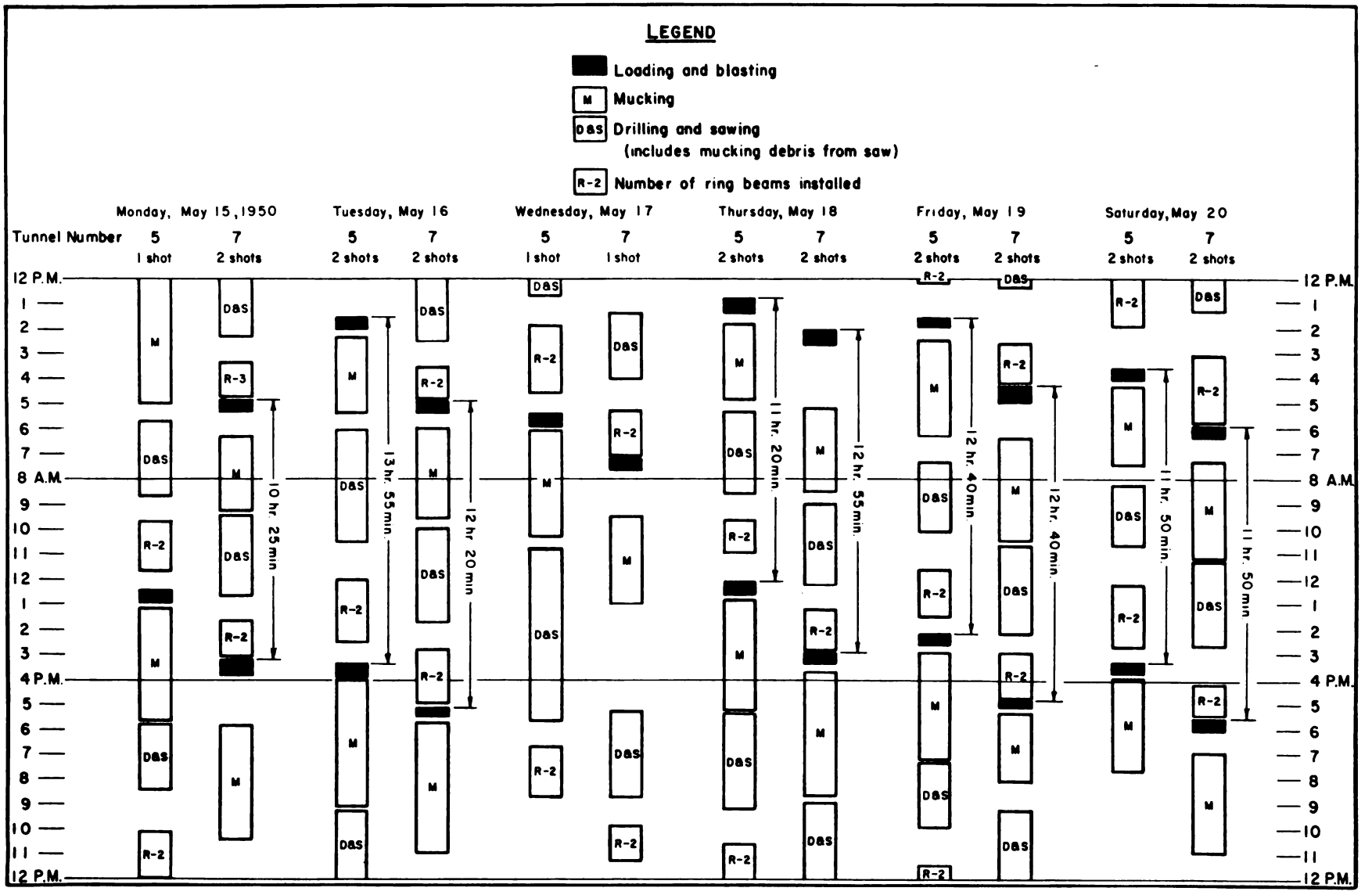

Figure 25. - Typical cycles for two-tunnel operation, peripheral sawing.

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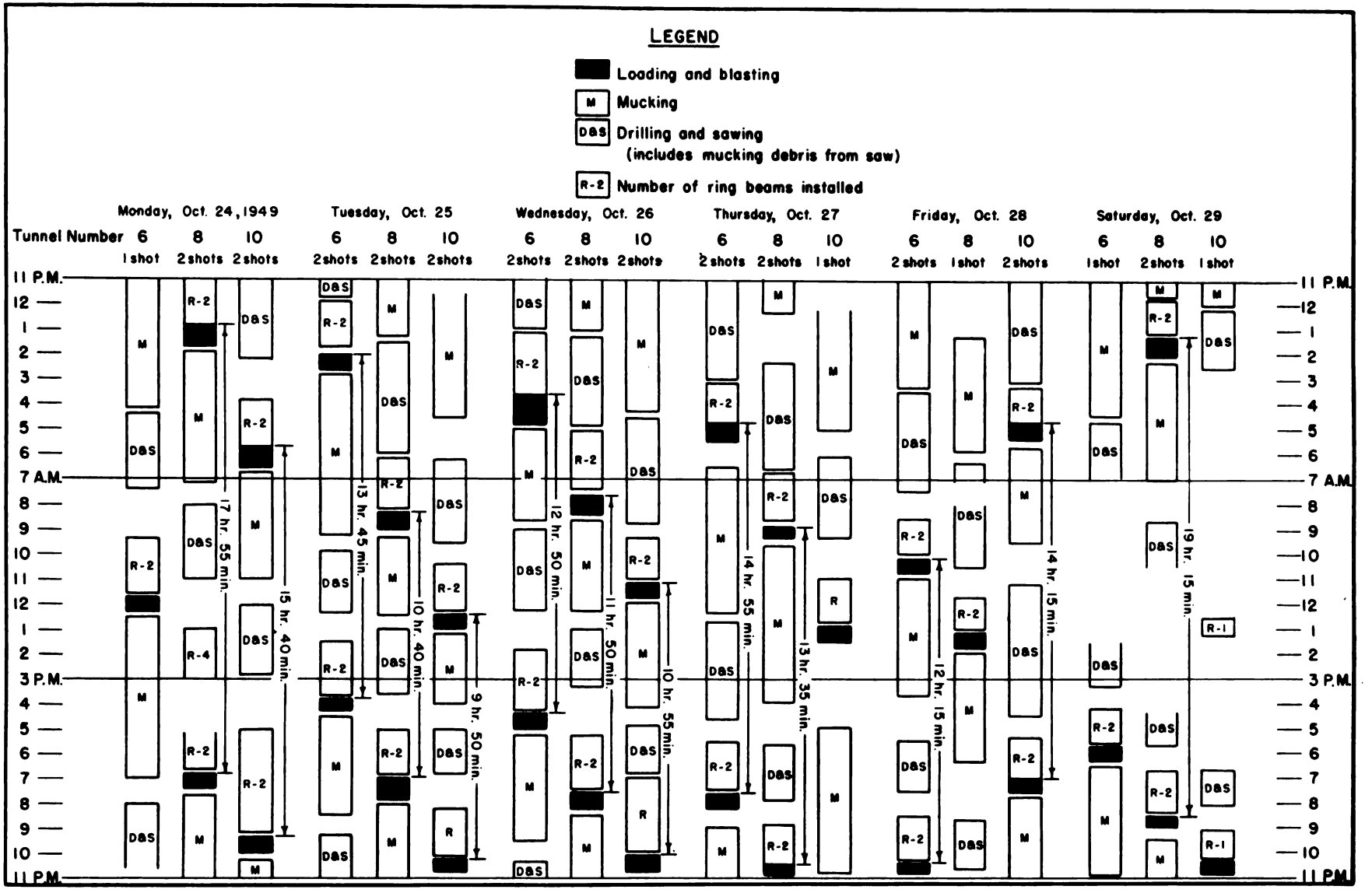

Figure 26. - Typical cycles for three-tunnel operation, peripheral sawing.

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TABLE 3.- Weekly and daily average advance from May 31, 1949 to September 16, 1950

Tunnels	Blast period From	Blast period To (incl.)	Weeks	Number of working days per week	Number of rounds per week	Weekly advance	Daily advance	Weekly advance cumulative
2	5/31/49	6/3/49	1	5	2	9	1.8	9
	6/6	6/11	2	6	4	25	4.2	34
	6/14	6/18	3	6	5	43	7.2	77
	6/20	6/25	4	6	6	66	11.0	143
2 - 4	6/28	7/1	5	6	8	57	9.5	200
	7/3	7/9	6	6	12	71.5	11.9	271.5
	7/11	7/16	7	6	13	104.5	17.4	376.0
	7/18	7/23	8	6	16	133	22.1	509
	7/25	7/30	9	6	15	125	20.8	634
Started saw experiment in #6	8/1	8/6	10	6	18	151	25.2	785
Peripheral drilling	8/8	8/13	11	6	18	146	24.3	931
	8/15	8/20	12	6	15	122	20.3	1053
2 -4 -6	8/22	8/27	13	6	15	130	21.7	1183
Peripheral sawing	8/29	9/3	14	6	17	149	24.8	1332
2 -4 -6 -8	9/4	9/10	15	6	19	164	27.3	1499
	9/12	9/17	16	6	21	168	28.0	1664
4 -6 -8	9/18	9/23	17	6	21	169	28.2	1833
	9/26	10/1	18	6	27	226	37.7	2059
4 -6 -8 -10	10/3	10/8	19	6	26	218	36.3	2277
6 -8 -10	10/10	10/15	20	6	28	223	37.2	2500
	10/17	10/22	21	6	30	243	40.5	2743
	10/24	10/29	22	6	31	256	42.7	2999
	10/31	11/5	23	6	33	272	45.3	3271
	11/7	11/12	24	6	30	230	38.3	3501
	11/14	11/19	25	6	31	260	43.3	3761
	11/21	11/26	26	6	28	246	41.0	4007
Stopped 6 & 8 middle of week	11/28	12/3	27	6	18	142	23.7	4149
10 -12 -1	12/5	12/10	28	6	15	127	21.2	4276
	12/12	12/17	29	6	13	115	19.2	4391
12 -1	12/19	12/23	30	6	17	146	24.3	4537
	12/27	12/31	31	6	22	188	31.3	4725
12 -1 -3	1/2/50	1/7/50	32	6	24	207	34.5	4932
	1/9	1/14	33	6	35	288	48.0	5220
	1/16	1/21	34	6	37	311	51.8	5531
	1/23	1/28	35	6	31	257	42.8	5788
	1/30	2/4	36	6	25	208	34.7	5996
	2/6	2/11	37	6	19	154	25.7	6150
1 -3	2/13	2/18	38	6	19	152	25.3	6302
	2/20	2/25	39	6	20	165	27.5	6467
	2/27	3/4	40	6	15	123	20.5	6590
	3/6	3/12						
	3/13	3/18	41	6	15	123	30.5	6713
1 -3 -5	3/20/50	3/25/50	42	6	9	69	11.5	6782
7 -3 -5	3/27	4/1	43	6	5	43	7.2	6825
	4/3	4/8	44	6	20	168	28.0	6993
	4/10	4/15	45	6	20	162	27.0	7155
	4/17	4/22	46	6	24	197	32.8	7352
	4/24	4/29	47	6	22	176	29.3	7528
5 -7	5/1	5/6	48	6	16	128	21.3	7656
	5/8	5/13	49	6	22	177	29.5	7833
	5/15	5/20	50	6	21	167	27.8	8000
	5/22	5/27	51	6	18	145	24.2	8145
	5/29	6/3	52	6	16	133	22.2	8278
	6/5	6/10	53	6	24	186	31.0	8464
	6/12	6/17	54	6	20	159	26.5	8623
7	6/19	6/22	55	4	10	77	19.2	8700
	6/26	6/30						
11 -9	7/5	7/8	56	4	8	69	17.2	8769
	7/10	7/15	57	6	21	174	29.0	8943
	7/17	7/22	58	6	23	185	31.2	9128
	7/24	7/29	59	6	25	200	33.3	9328
	7/31	8/5	60	6	22	173	28.8	9501
9	8/7	8/12	61	6	16	128	21.3	9629
11	8/14	8/19	62	6	16	129	21.5	9758
9 -11			63	6	17	138	23.0	9896
	8/28	9/2	64	6	17	134	22.3	10030
	9/5	9/7	65	6	7	47	7.8	10077
	9/12	9/16	66	6	11	88	14.7	10165
Total average				391	1245	154	26.0	

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Typical cycles from load and blast to load and blast in a one-tunnel operation, using the peripheral or line-drilling method are shown in figure 23. The cycle for a representative week is shown on the graph curve, figure 22; also, table 3 shows that for the week of June 20 through June 25, 1949, the number of rounds was 6, the weekly advance was 66 feet, and the daily average advance was 11 feet. As can be seen by table 3, the 66-foot advance is above the average for a one-tunnel operation. The cycle time ranged from 18 hours to 27 hours 55 minutes. An arithmetical average of the cycle periods is 22 hours 14 minutes.

Typical cycles in a 2-tunnel operation using line drilling are shown in figure 24. The corresponding period is shown on table 3 from July 25 through July 30, 1950. Fifteen rounds were drilled and blasted with a weekly advance of 125 feet and a daily average of 20.8 feet. As can be seen by the graph curve (fig. 22), the period is fairly representative of a 2-tunnel operation. In contrast, the period in figure 23 was above average, yet the weekly advance in the 2-tunnel operation is almost double that of the one-tunnel operation. Only four of the cycle times are shown in figure 24, but the time range from load and blast to load and blast for both tunnels is 16 hours 55 minutes to 23 hours 15 minutes. An arithmetical average of the cycle periods is 19 hours 16 minutes, a reduction of 2 hours 58 minutes under the cycle time for a one-tunnel operation where an advance of 66 feet was made during the week.

Typical cycles from load and blast to load and blast in a 2-tunnel operation employing peripheral sawing are shown in figure 25. The corresponding period can be seen on the graph curve (fig. 22) and table 3 in the period from May 15 through May 20, 1950. During the period, 21 rounds were blasted. The weekly advance was 167 feet, and the daily average advance was 27.8 feet. The period selected is representative of a 2-tunnel operation. Especially to be noted in this bar graph, as compared with the graphs in figures 23 and 24, is the shorter length of the bars for each part of the cycle of operations. The drilling and sawing period is considerably shorter than the drilling period; also, the time required for setting the rings has been shortened, and the load and blast period is shorter. Mucking time, also, has been reduced.

The duration of a complete cycle in a 2-tunnel operation employing peripheral sawing ranges from 10 hours 25 minutes to 20 hours 40 minutes. Only those cycles that are completed within 1 day are shown in figure 25. An arithmetical average of the total time for the cycles during the week is 13 hours 34 minutes. Cycle time was reduced 5 hours and 42 minutes under the average for a 2-tunnel operation advanced by peripheral or line drilling.

Figure 26 is a bar graph of a 3-tunnel operation by peripheral sawing. The corresponding period is shown on the graph curve (fig. 22) and table 3 in the period from October 24 through October 29, 1949; 31 rounds were blasted in the period with a weekly advance of 256 feet and a daily average of 42.7 feet. As can be seen by the graph curve (fig. 22), the period is representative of a 3-tunnel operation.

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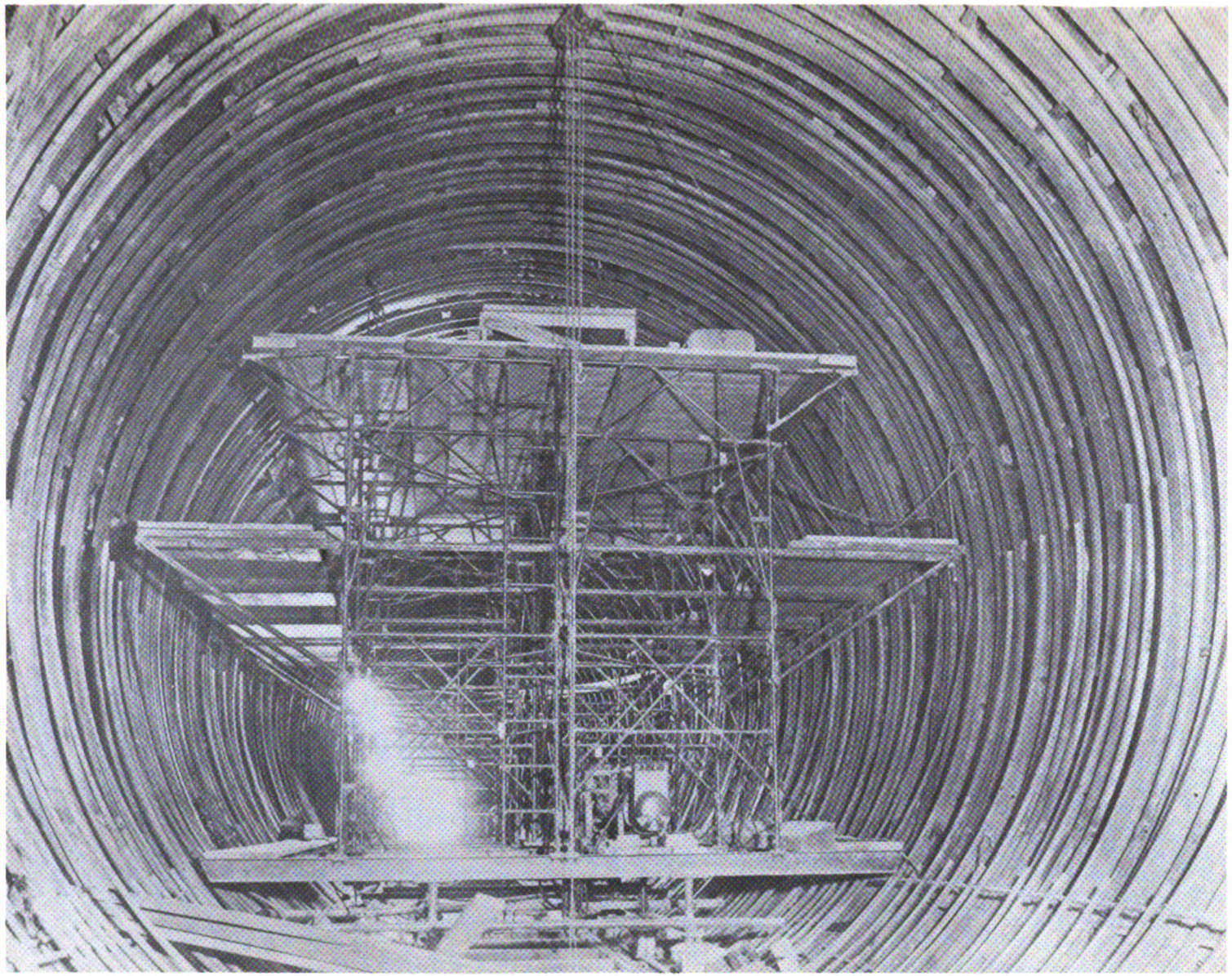

Figure 27. - Jumbo used for erecting and welding reinforcing steel.

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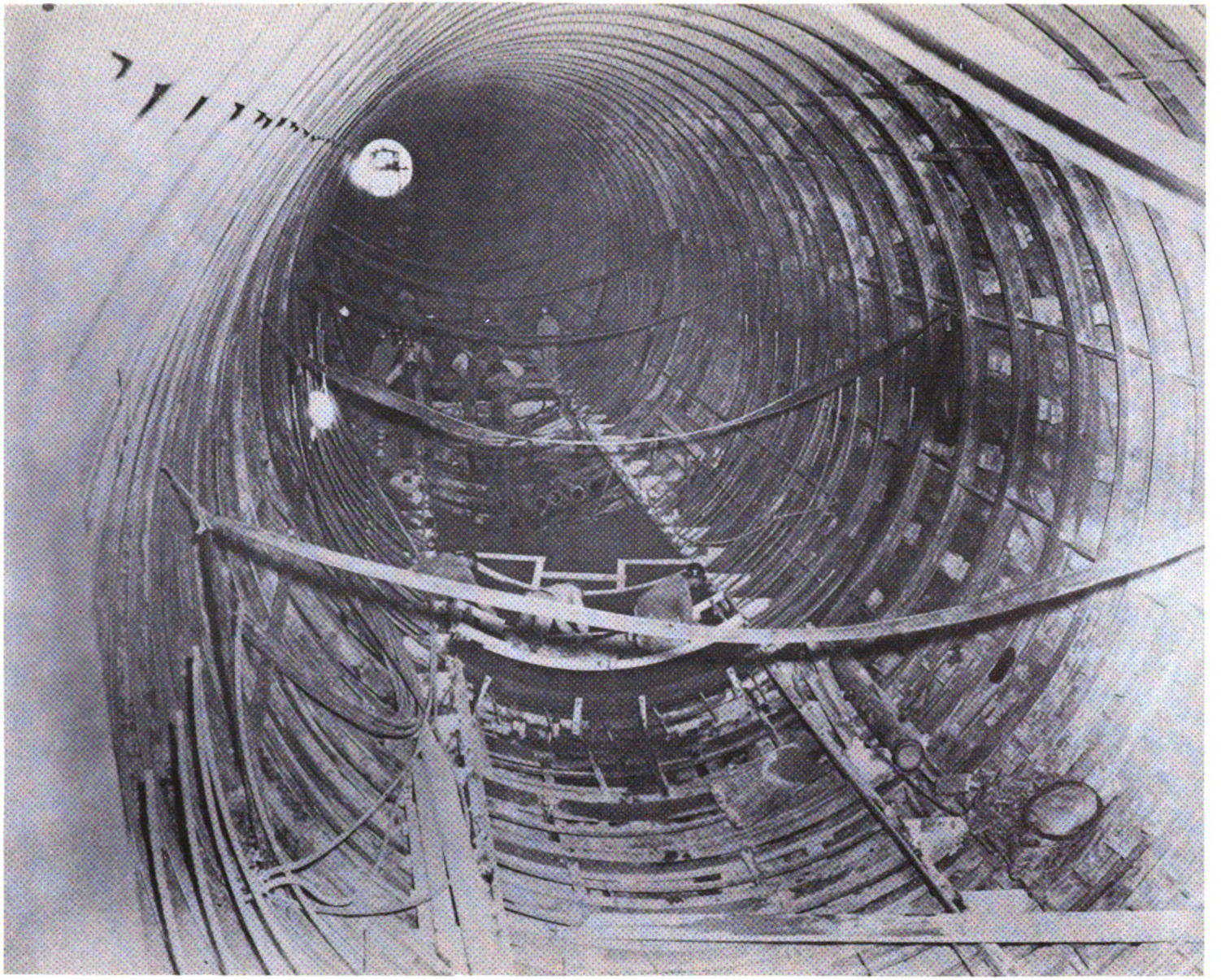

Figure 28. - Pouring and shaping alternate inverts.

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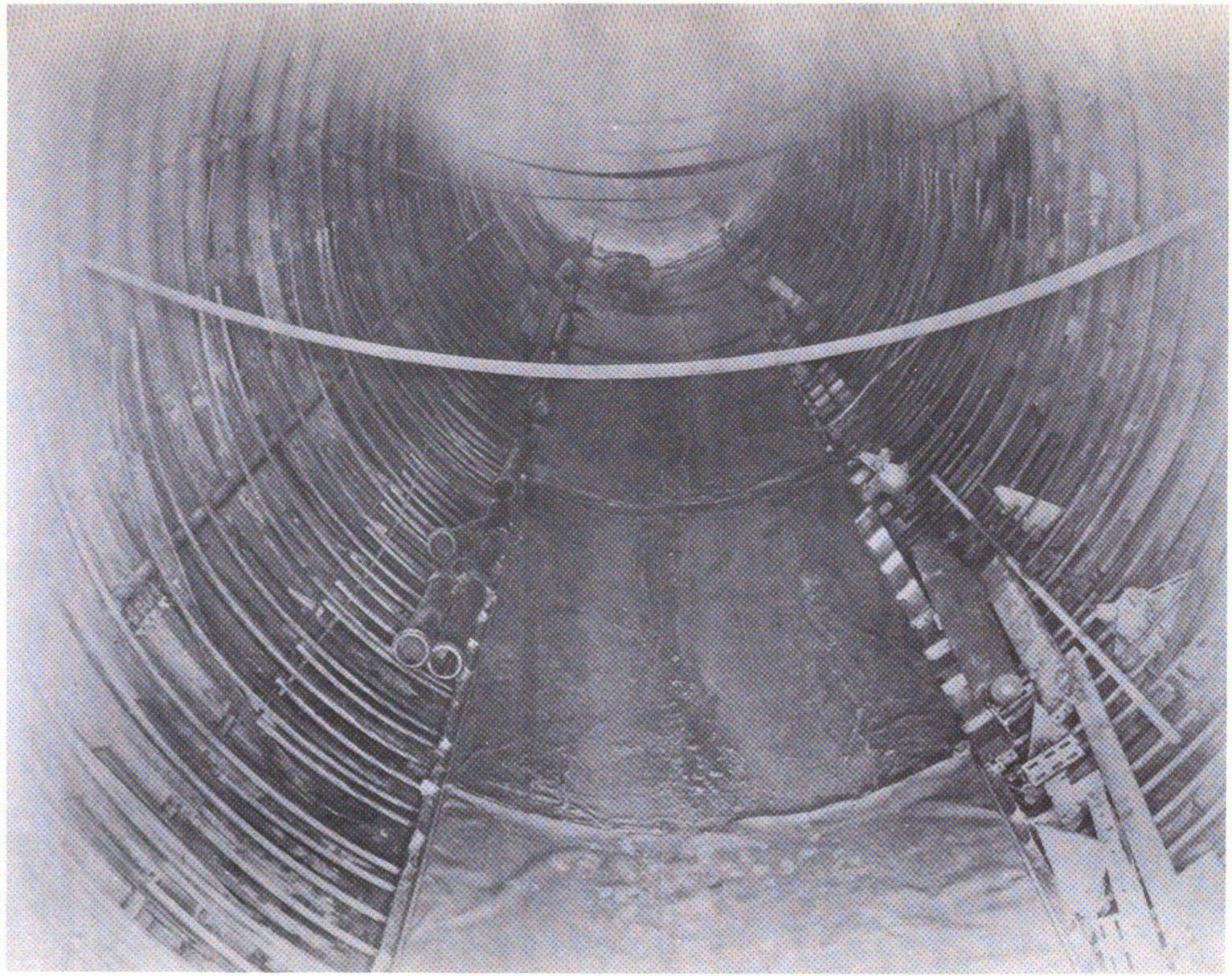

Figure 29. - Completed concrete invert.

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From 4 to 6 shots were made each day in the 3 tunnels. In this graph, as in the preceding one (fig. 25), the time for sawing and drilling, setting rings, loading and blasting, and mucking has been shortened considerably over that required for the 2-tunnel operation using peripheral or line drilling. The cycle of operations time ranges from 9 hours 50 minutes to 19 hours 20 minutes. The arithmetical average is 14 hours 13 minutes. Machinery breakdowns on the last day of the week tended to increase the average cycle time. These breakdown periods can be seen in figure 26 under the heading "Saturday," where the bars are open and the time between open bars is long.

During periods shown in table 3 in the 3-tunnel operation where the weekly advance was more than 256 feet, the average time for the cycle of operations probably dropped below 14 hours and 13 minutes; conversely, where the weekly advance was less than 256 feet, the average cycle time was more than 14 hours and 13 minutes. The average time in the 3-tunnel operation is 39 minutes more than the average time for a complete cycle in the 2-tunnel operation, where peripheral sawing was employed; however, the weekly advance was 256 feet in the former, as compared with 167 feet in the latter. This 89-foot greater advance resulted from carrying the cycles in three tunnels rather than two. The footage gained each week assisted the contractor in maintaining his schedule.

CONCRETE LINING

The total length of a tunnel is driven and supported with steel before the reinforced-concrete lining is poured. Final preparation of walls and invert for concreting is slow and tedious. Cleaning starts from the upstream end. The wooden deck and mucker rail are removed as the work progresses toward the downstream end. The invert is cleaned by hand mucking onto a belt conveyor and thence to a truck. Final cleaning is done with an industrial vacuum cleaner. In addition to the tunnel-support ring beams laid in the second part of the cycle of operations, two rings of reinforcing bars spaced on 1-foot centers are erected from a jumbo. Figure 27 shows the jumbo used for erecting and welding the reinforcing steel.

Concrete pours with Pumpcrete equipment begin at the transition area of each tunnel and progress both ways and also from the downstream end progress upstream, with a closure midway in the large-diameter tunnel. The concrete mixing plant is on the upper bench above the tunnels, and the concrete is pumped into the downstream end of the tunnels through 8-inch pipe. The pipe is joined by the standard toggle clamp used with Pumpcrete equipment.

The invert, which includes the lower 60 degrees of the circular lining, is poured in 24-foot alternate blocks. Because of the low angles involved, no fixed form is required. Inverts are screeded with a movable form. Figure 28 shows alternate inverts being poured and finished, and figure 29 shows the completed concrete invert.

After the inverts have been cured sufficiently, track is laid for steel forms. In preparation for the arch pour, the invert joint is sand blasted and further cleaned by shovel, trowel, and vacuum cleaner. The arch pour is

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made into a movable expanding form. Two forms are required for any one tunnel - one for the smaller- and one for the larger-diameter portions of the tunnel. The arches are poured successively in 24-foot blocks. The expanding form is anchored at the desired location, and a mobile concrete pump running on rail is placed under it. The concrete is pumped into this pump from the plant on the surface, and the pump in turn transfers the concrete into the form.

Prior to the actual pouring of the concrete, the expanding form has been set securely into position, and the free end is bulkheaded with timber. This requires careful carpenter work, and considerable time is consumed in the operation. The timber bulkheads must be notched around the reinforcing steel and made tight to retain the concrete within the form. Concrete is allowed to set 12 to 16 hours before the expanding form is removed.

Three tunnels are in the process of being lined at any given time. Concreting is on a definite cycle of operations, just as are the tunnel excavations. After the concrete has set, the form is advanced ahead to the next 24-foot block. Equipment, such as the pump for pumping the concrete into the expanding form, and general supplies are brought into the tunnels by a battery locomotive. The locomotive services all three tunnels.

When the expanding form is removed from the block after a setting time of 12 to 16 hours, the hardened concrete is kept continuously wet for 14 days. The face of adjoining tunnels that are in the process of being driven must be 100 feet behind 7-day-old concrete in the holed tunnel.

SAFETY FEATURES

In addition to the safety precautions taken during blasting, many other safety features are used in both driving the tunnels and concreting. There has been serious danger in some of the tunnels from rock falls. These falls occur after the round has been blasted and are caused by rocks slipping out of the crown, usually on the side of the tunnel nearest the river. The rocks slip out along seams, and usually there is no warning of any kind prior to the fall.

The rock-fall problem was solved jointly by the Corps of Engineers and Silas Mason Co. The Engineers made the basic suggestion of screening off the crown so that workmen would not be working under open ground, and J. C. Drummond, engineer with the Silas Mason Co., designed the protective canopy to cover the open crown. Two detailed drawings of the canopy are shown in figures 30 and 31, and figure 32 is a picture of the canopy.

The canopy is made in two different sizes, one to fit the larger bore section and the other to fit the smaller bore section. The detailed drawings show the size of the screen for the small section and the method by which it is placed in position on I-beam tracks. The I-beam tracks are bolted to the tunnel-supporting ring beams on each side of the crown of the tunnel.

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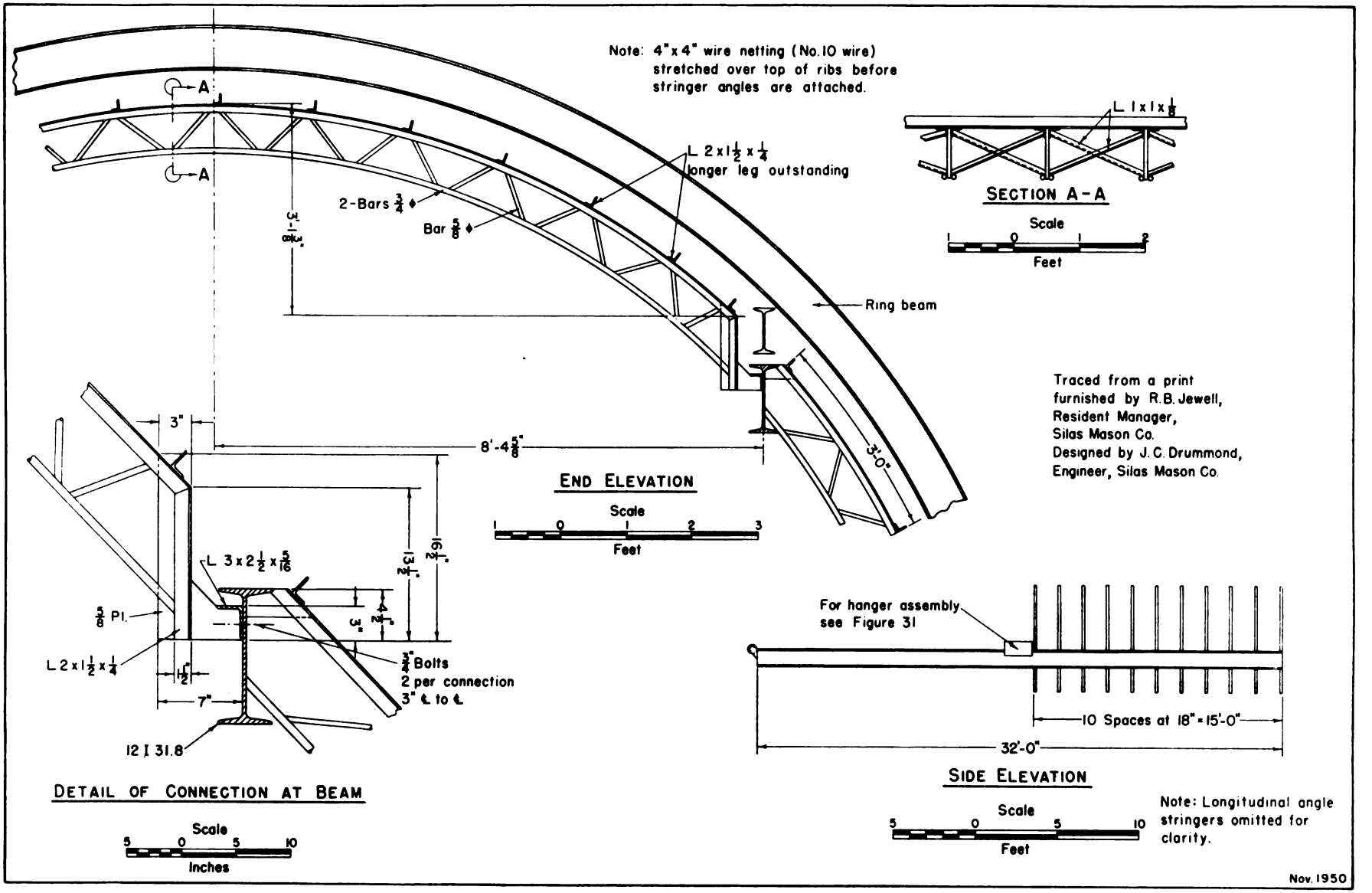

Figure 30. - Canopy for 22-foot diameter tunnels.

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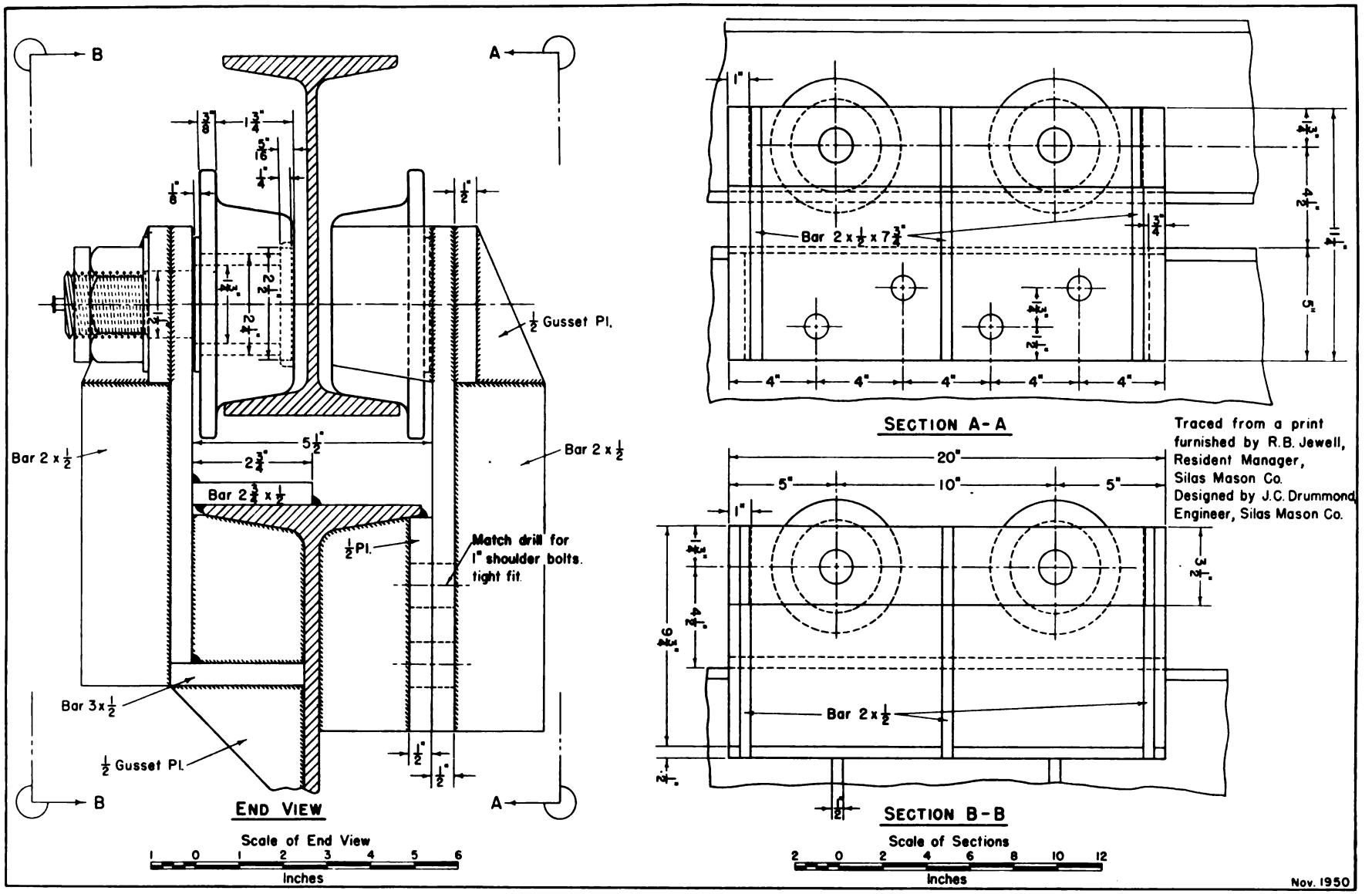

Figure 31. - Hanger assembly for small canopy.

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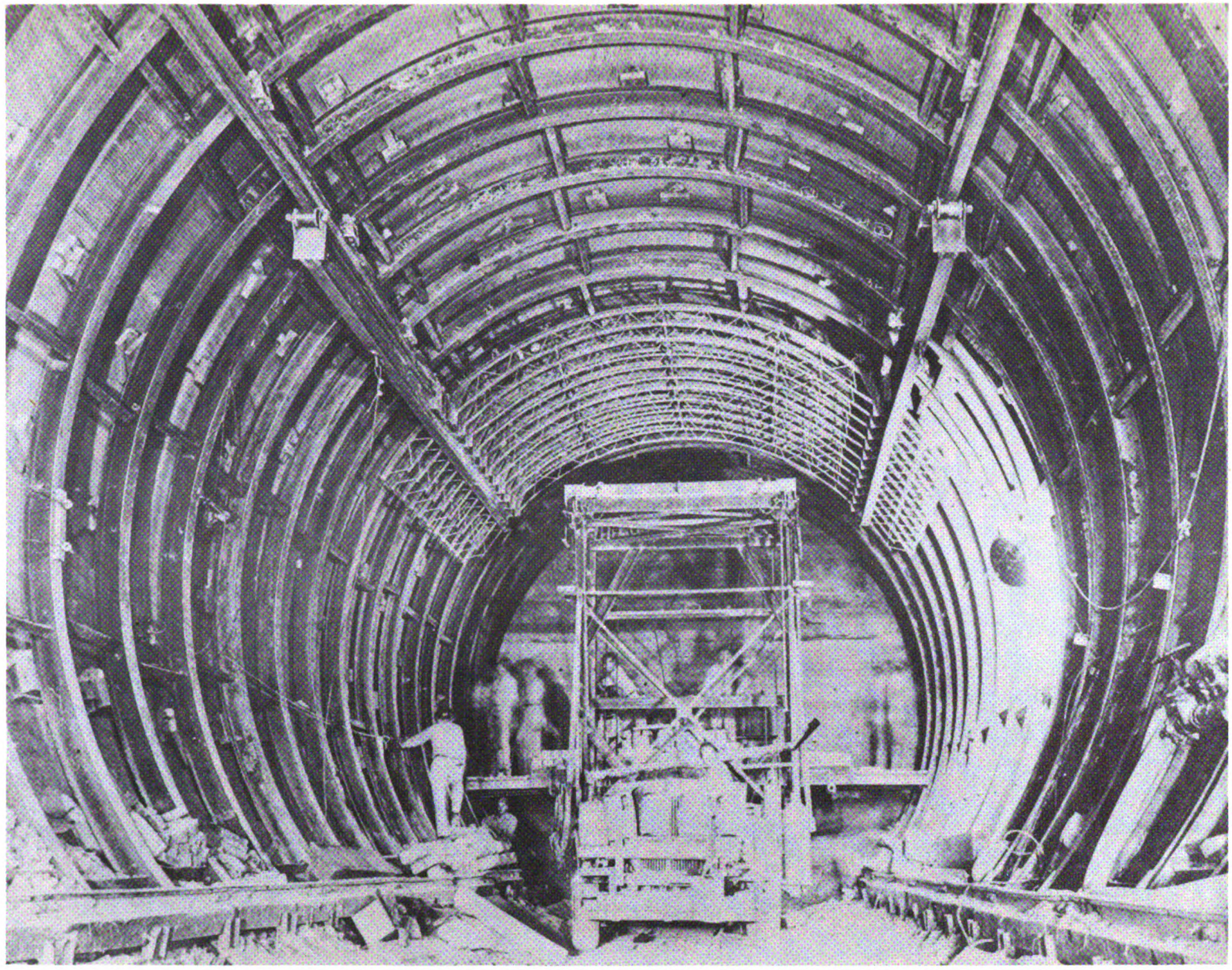

Figure 32. - Protective canopy in the heading of a small-bore section.

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Figure 30 shows an end elevation, side elevation, and detail of the connection at the I-beam that supports the screen. The canopy is concentric, and the other half would be the same as the half drawn. As can be seen from the drawing, the canopy portion is 15 feet long, with an over-all length of 32 feet, including the supporting beams. The covering consists of a wire netting stretched over the top of a series of reinforced braces spaced on 1-foot 6-inch centers. The screen is held down by stringer angles.

Figure 31 shows the hanger assembly and the manner in which it rides on the I-beam tracks that are attached to the tunnel-supporting ring beams. The hanger assembly is immediately back of the wire netting that serves as the covering over the open ground. The location can be seen in the side elevation in figure 30. The assembly consists generally of two wheels that ride on the inside flanges of the I-beam tracks. Attached to and hanging from the wheels are steel plates supported by bars. The plates are attached to the I-beam supporting the canopy.

The canopy-supporting I-beam also has a roller on the back end (see side elevation, fig. 30), which rides on the flat surface of the I-beam track. When the canopy is pushed toward the face, the screen will be under the open crown of the tunnel, and the screen-supporting I-beam will be overhung 15 feet from its hanger assembly support. The supporting I-beam is under a cantilever load, the hanger assembly being the pivotal point. The back roller resting against the flat surface of the track will have an upward thrust against the I-beam track.

The I-beam track is attached to the tunnel-supporting ring beams by bolts and plates fastened to the flanges of both beams. The track bolted in position can be seen in figure 32. The track is composed of 6- and 9-foot sections of I-beams that are removable as the tunnel face advances. As the face is advanced in the tunnel and tunnel-supporting ring beams are set in place, sections of the I-beam track are removed from the back end and set in place at the front end; thus, the track is kept continuously advanced with the face of the tunnel.

The protective canopy is easily moved into position by the use of cables attached to the canopy-supporting I-beam. These cables can be seen in figure 32 - one on the left hangs straight down, and another on the right hangs on the tunnel-supporting ring beams. By the use of these cables the canopy can be pulled either forward or backward.

Although the canopy will not withstand large rock falls from the crown, it acts as a shield to deflect rocks or give warning that they are slipping out of the crown. The canopy has served to give sufficient warning to allow the workmen to clear the face and move back under supported ground before falling rocks break through the screen.

Interior - Bureau of Mines, Pittsburgh, Pa.

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